LANDSLIDES AND MASS-WASTING

- *Murck et al. 1996: Environmental Geology. John Wiley & Sons, Inc.*
- *Montgomery 1995: Environmental Geology. Wm. C. Brown Publishers*

MASS-WASTING AND ITS HUMAN IMPACTS

- The landscapes we see about us may appear fixed and un-changing, but if we were to make a time-lapse motion picture of almost any slope it would be clear that the slope is constantly changing. Much of the recorded motion would be a result of **mass-wasting,** the movement of Earth materials downslope as a result of the pull of gravity.
- *Any perceptible downslope movement of bedrock, regolith, or a mixture of the two is commonly referred to as a* ***landslide.***

Landslide

- Rapid slide of large mass of bedrock.
- Often occurring on steep mountain slopes.

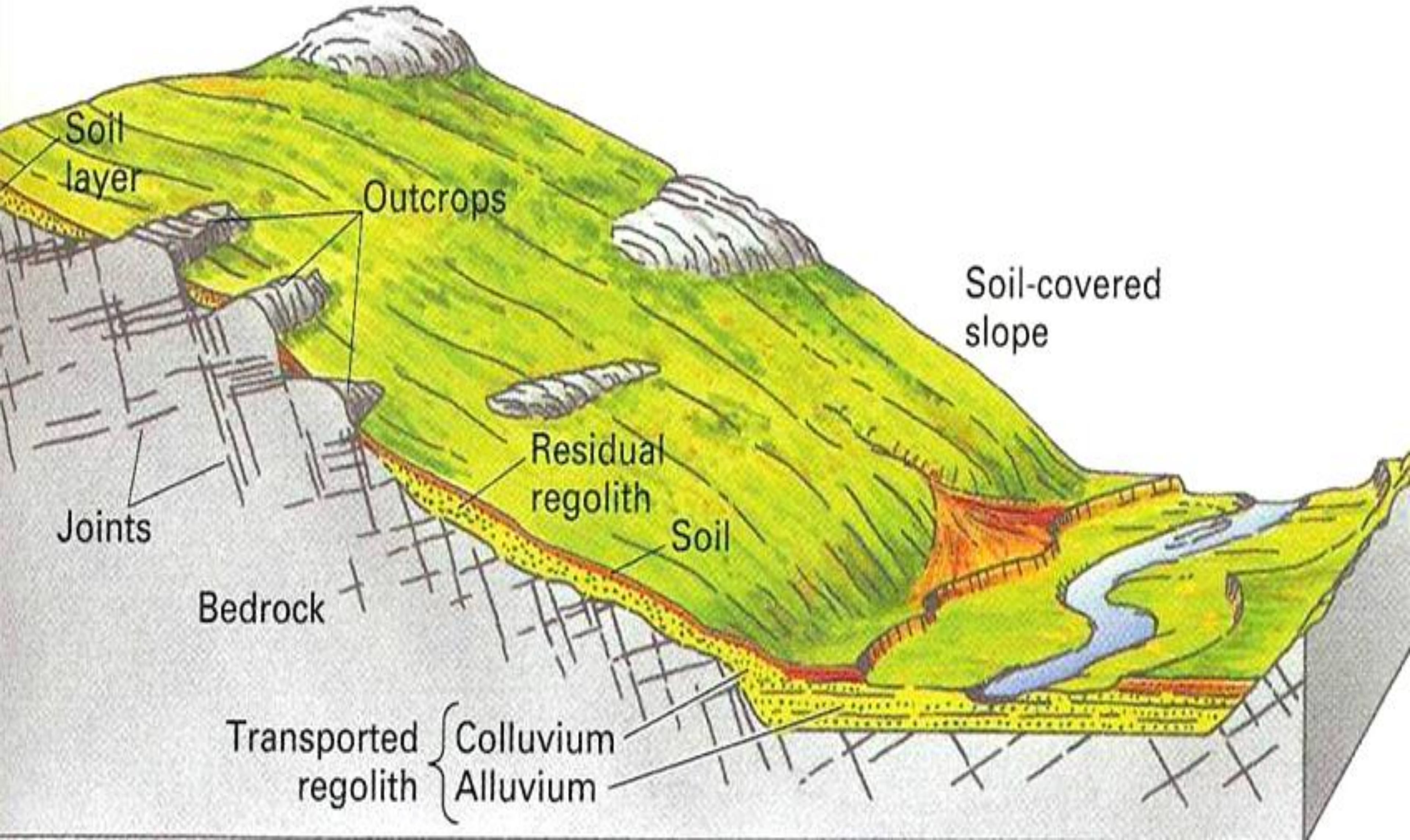
Remember

Mass Wasting

- **Spontaneous downward movement of soil, regolith, or bedrock due to gravity.**
- **Soil**: Unconsolidated, naturally occurring, < 2 mm diameter, at surface, variable depth.
- **Regolith**: Layer of unconsolidated rock overlying bedrock. Residual or transported.
- **Bedrock**: Consolidated rock.

Remember

Soil, Regolith, & Bedrock



TYPES OF MASS-WASTING PROCESSES

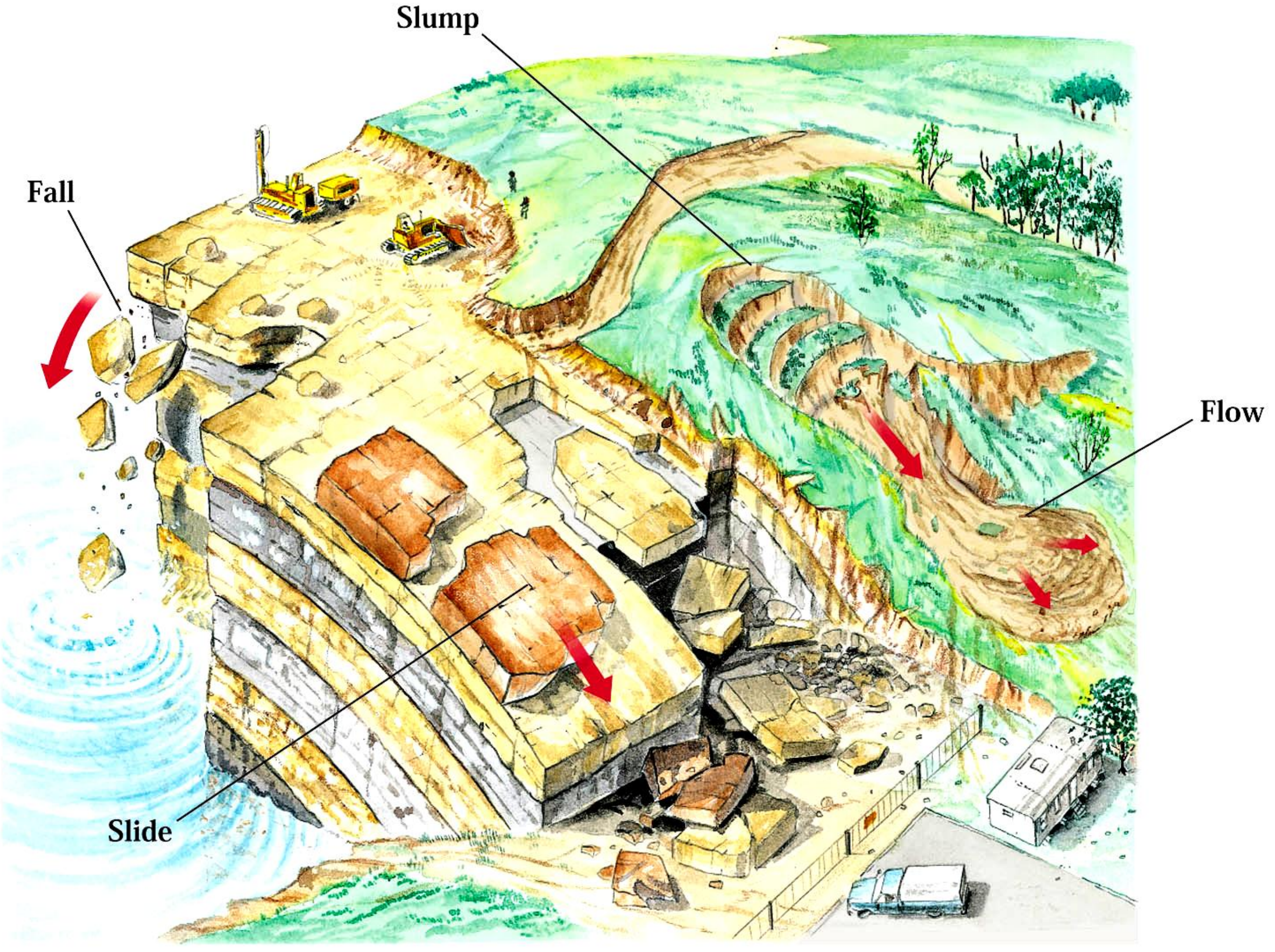
- All mass-wasting processes take place on slopes. There are many kinds of slope movements, but there is no simple way to classify such movements. **The composition and texture of the material involved, the amount of water or air in the mixture, and the steepness of the slope** all influence the type and velocity of movement.

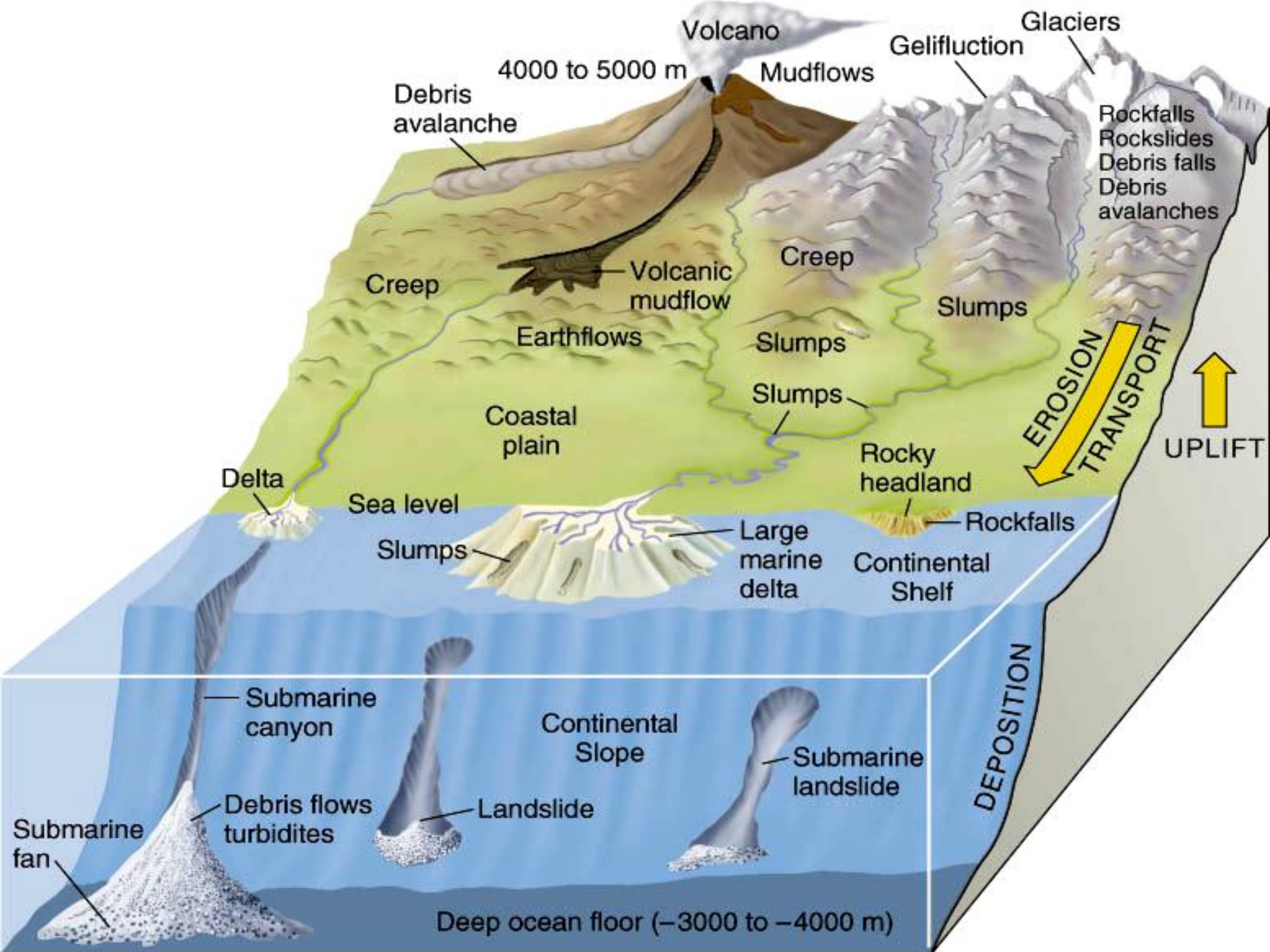
Types Of Mass-Wasting Processes

- For the purposes of this discussion, we will divide mass wasting processes into two basic categories:
- (1) those involving the sudden failure of a slope, which results in the downs-lope transfer of relatively coherent masses of rock or rock debris by **slumping**, **falling**, or **sliding**; and
- (2) those involing the downslope flow of mixtures of sediment, water, and air.
- In the latter category, which involves internal motion of flowing masses of debris, processes are distinguished on the basis of their velocity and the amount of water in the flowing mixture. This approach to the classification of mass movements is outlined in Table 6.2.

T A B LE . 6.2 . Outline for Classification of Types of Mass- Wasting Processes

Slope failures	***Sediment flows***	***Mass-wasting in cold climates***	***Subaqueous mass-wasting***
Slumps	**Slurry flows** Solifluction Debris flows Mudflows	Frost heaving	Slumps
Falls Rockfall Debris fall		Gelifluction	Slides
Slides Block glide Rockslide Debris slide	**Granular flows** Creep Earthflows Grain flows Debris avalanches		Flows


Slump
Fall
Flow
Slide



Volcano
Glaciers
Gelifluction
4000 to 5000 m
Mudflows
Debris avalanche
Rockfalls
Rockslides
Debris falls
Debris avalanches
Creep
Volcanic mudflow
Creep
Slumps
Earthflows
Slumps
Slumps
EROSION
TRANSPORT
Coastal plain
UPLIFT
Rocky headland
Delta
Sea level
Rockfalls
Large marine delta
Slumps
Continental Shelf
DEPOSITION
Submarine canyon
Continental Slope
Submarine landslide
Debris flows turbidites
Landslide
Submarine fan
Deep ocean floor (–3000 to –4000 m)

Slope Failures

- The constant pull of gravity makes all hillslopes and moutain cliffs susceptible to failure. When failure occurs, material is transferred .downslope until a stable slope condition is reestablished. Some of the most common types of slope failure are illustrated in Fig. 6.1.
- **(1)Slumps**
- **A slump** is a type of slope failure involving *rotational* movement of rock or regolith, that is, downward and outward movement along a curved, concave-up surface (Fig. 6.1). Slumps can range from small displacements covering only one or two square meters to large complexes that cover hundreds or even thousands of square meters.

Slumps

- Slumps frequently result from artificial modification of the landscape. They are common along roads and highways where bordering slopes have been oversteepened by construction activity.

Falls

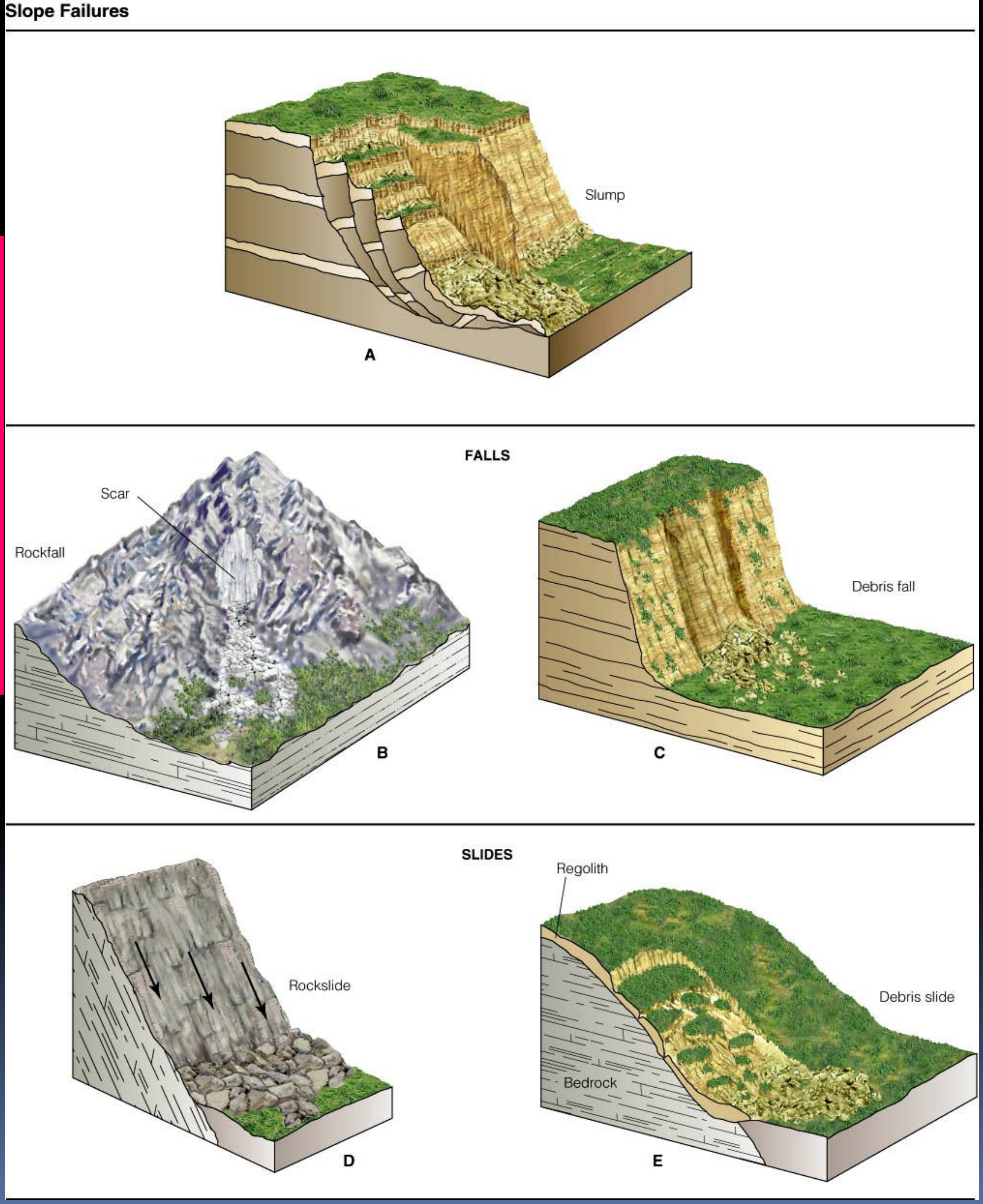
- If you ask mountain climbers about the greatest dangers associated with their sport, they are likely to place falling rock near the top of the list. A **fall** is a sudden, vertical movement of Earth material, for example, from an overhanging cliff.

Slump

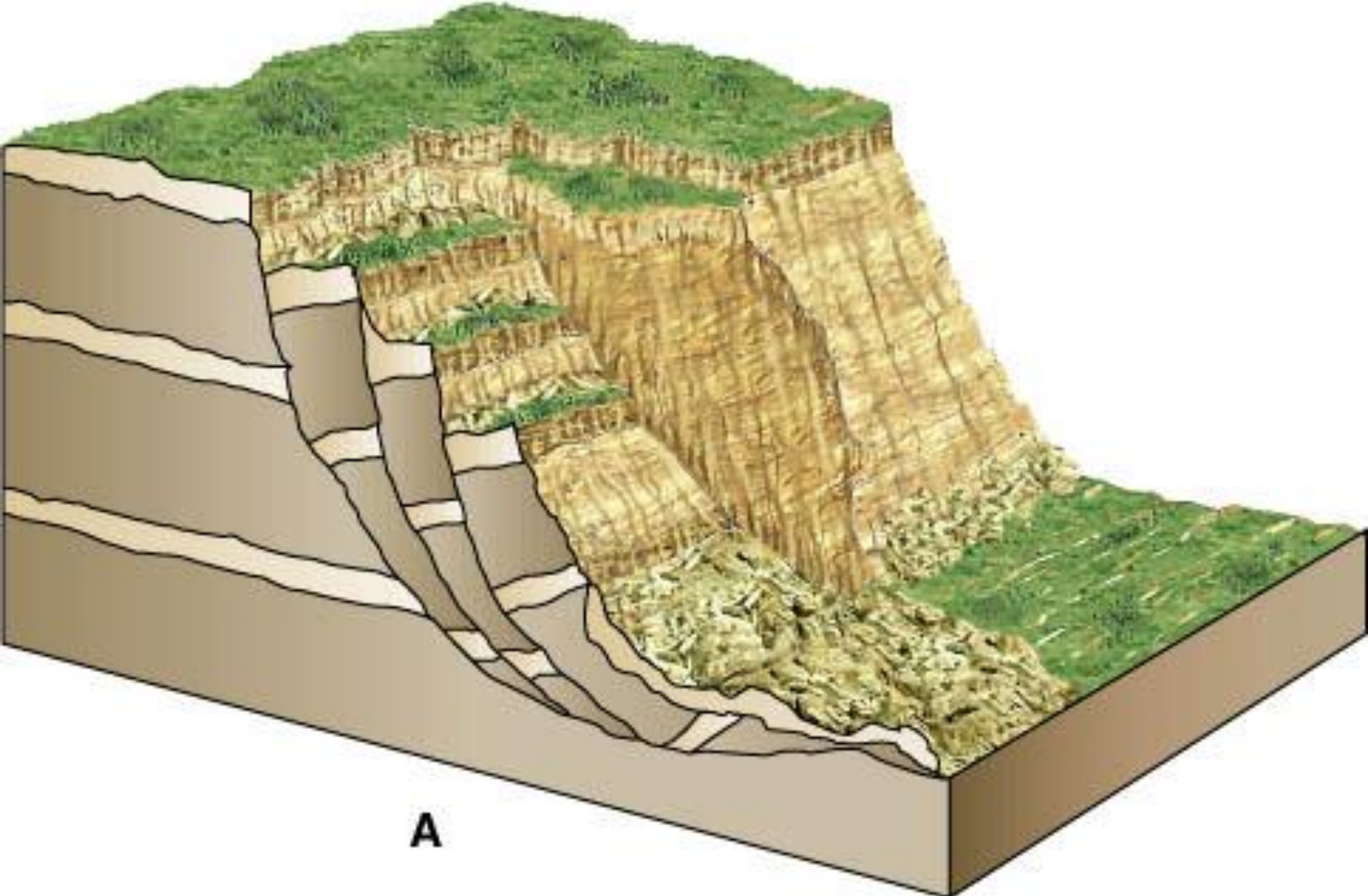
Backward rotation. Initiated by undercutting of slope.


Large slump in central Washington

A FIGURE 6.1 Examples of slope failures giving rise to slumps, falls, and slides.



SLUMP



A

Could the property losses in Kelso have been prevented?

Slumps from the Kelso, WA Landslides

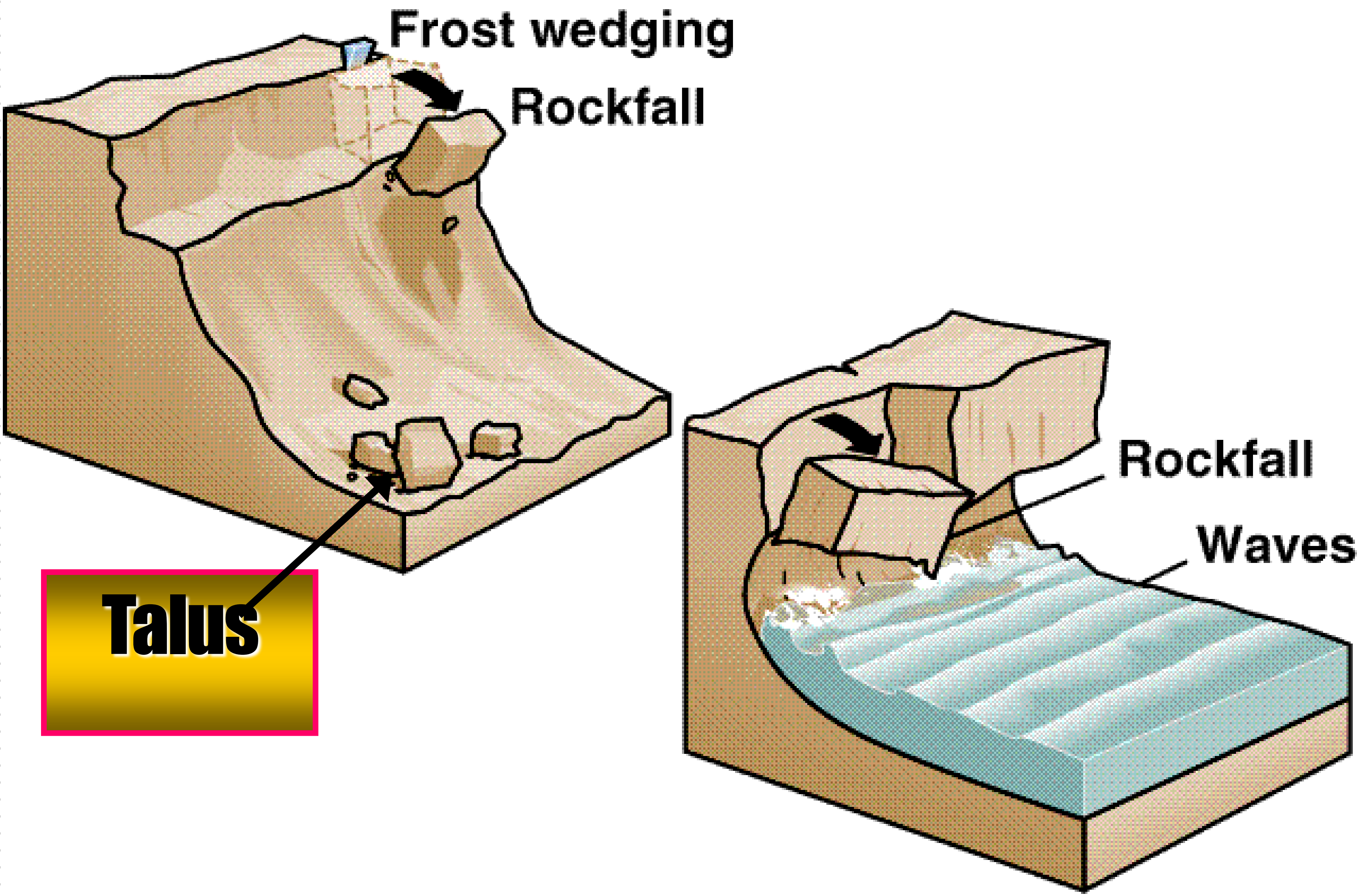
Slumps permit further access to soil by water.

The appearance of surface ruptures such as slumps are one indicator of potential big mass wasting trouble ahead.

Falls

- ***Rockfall,*** the free fall of detached bodies of bedrock from a cliff or steep slope, is common in precipitous mountainous terrain, where rockfall debris forms conspicuous deposits at the base of steep slopes (Fig. 6.1).
- As a rock falls, its speed increases. If we know the distance of the fall *(h),* we can calculate the velocity *(v)* on impact as
- $V = 2gh$
- where *g* is the acceleration due to gravity. What this formula tells us is that a rock of a given size will be traveling at a much higher velocity if it falls from a point high on a steep mountain face than if it falls from a low cliff.

Two Examples of Rockfall



Watch for fallen Rocks

Falls

- A rockfall may involve the dislodgement and fall of a single fragment or the sudden collapse of a huge mass of rock that plunges hundreds of meters, gathering speed until it breaks into smaller pieces on impact. The pieces continue to bounce, roll, and slide downslope before friction and decreasing slope angle bring them to a halt. Sometimes not only rock but overlying sediment and plants are dislodged.

  The resulting ***debris fall*** *is* similar to a rockfall, but it consists of a mixture of rock and weathered regolith as well as vegetation (Fig. 6.1).

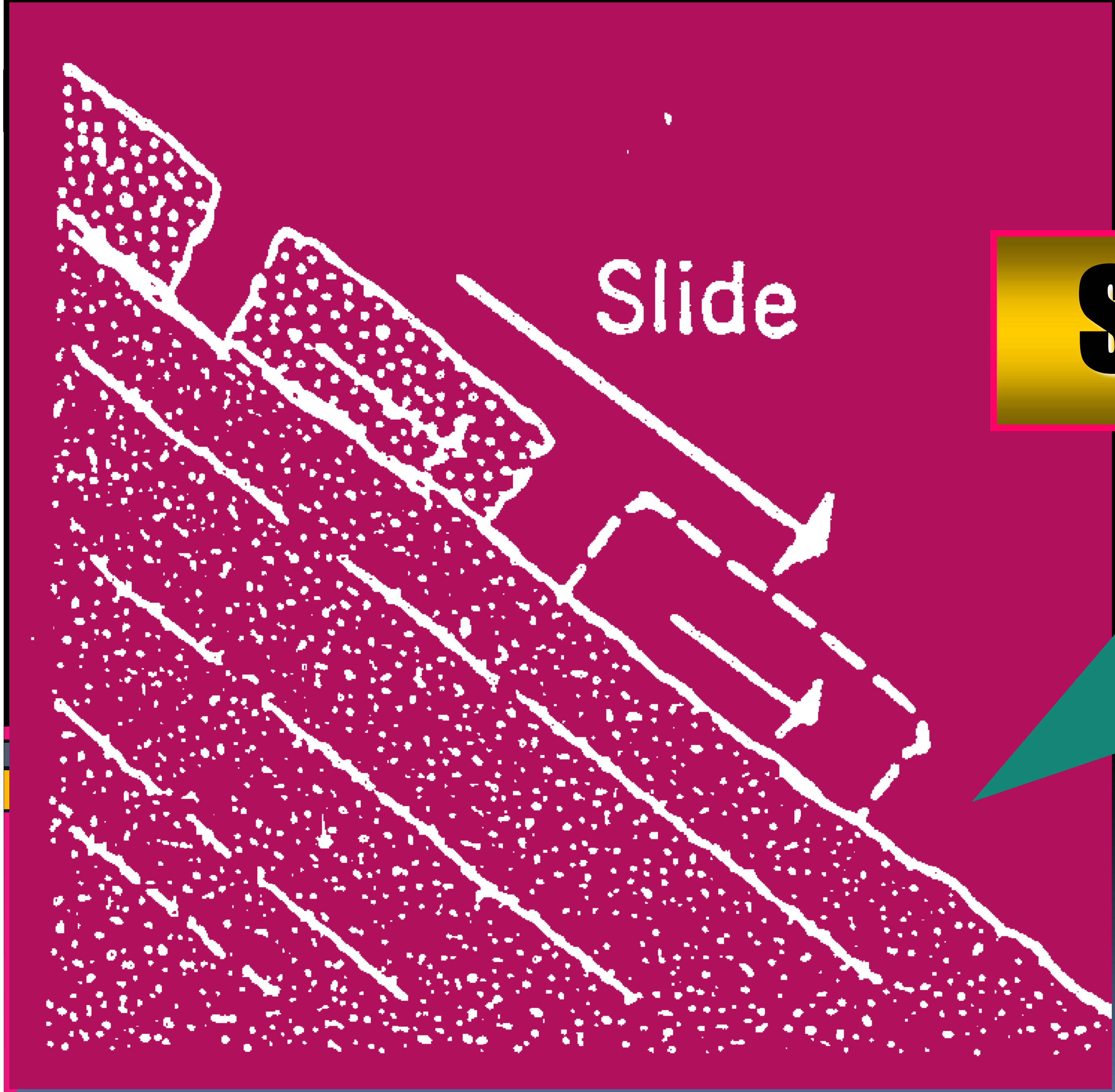
Slides

- **Slides,** like slumps and falls, involve the rapid displacement of masses of rock or sediment. In slides the movement is *translational,* that is, uniform movement in one direction with no rotation. ***Translational slides*** are also called **block glides** because they involve the movement of relatively coherent blocks of material along well-defined, inclined surfaces such as faults, foliation planes (in metamorphic rocks), or layering (in sedimentary rocks or alternating sequences of rock types).
- A ***rockslide*** is the sudden downslope movement of detached masses of bedrock (or of debris, in the case of a ***debris slide)*** (Fig. 6.1). Like falls, rockslides and debris slides are common in high mountains where steep slopes abound.

Slides

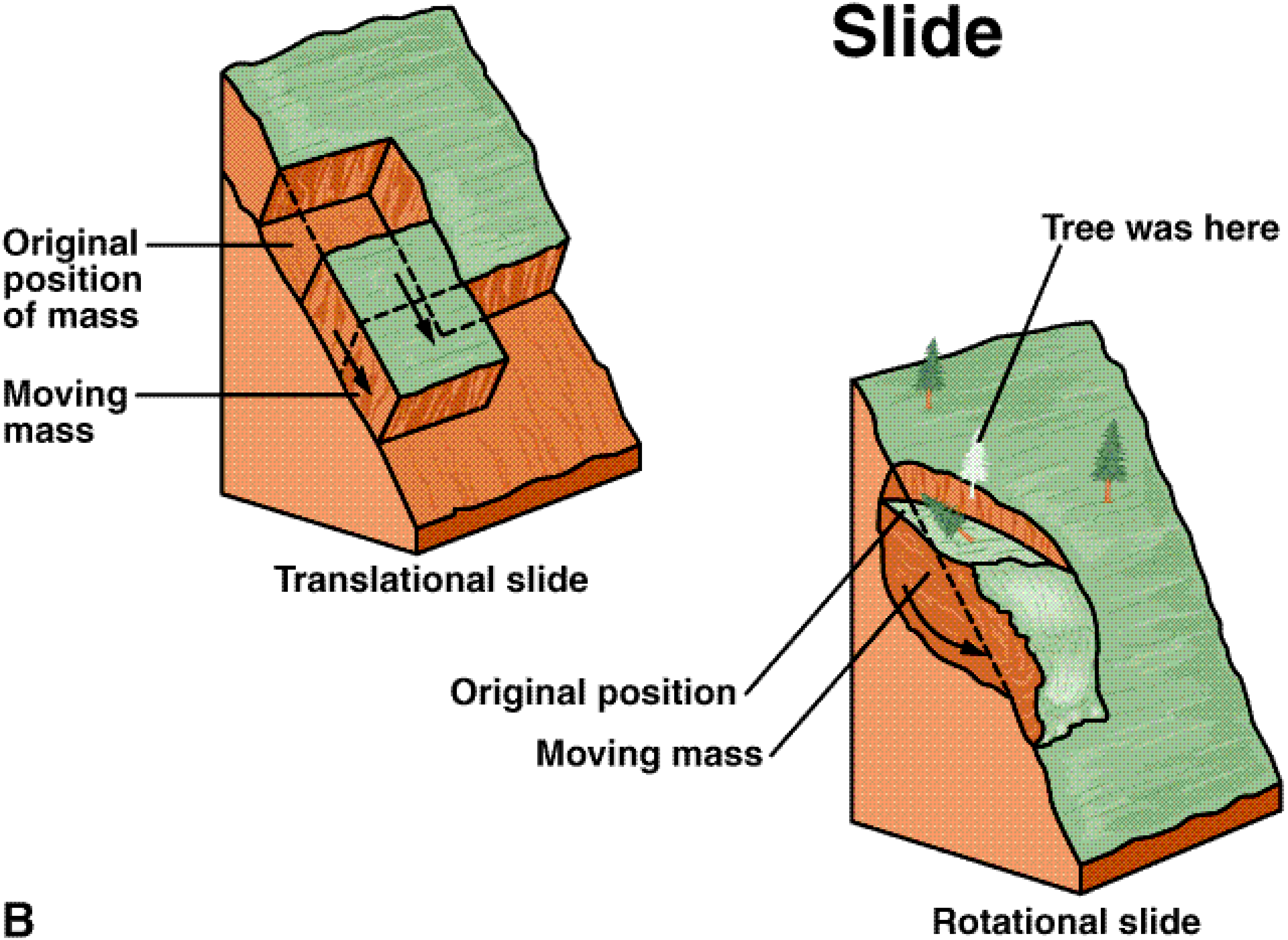
- Top and bottom of material move at same rate.
- Little deformation during movement.
- Slip plane is present.

Remember



Slide

Slide


Original position of mass
Moving mass
Translational slide
Tree was here
Original position
Moving mass
Rotational slide
B

Slides

This is a typical landslide. Note that materials hold together in more-or-less singular blocks.

As is common, when the slide blocks reach a lower slope, they break up (becoming a debris flow in this case).

The La Conchita landslide, near Santa Barbara, CA, Spring, 1995.

Flows

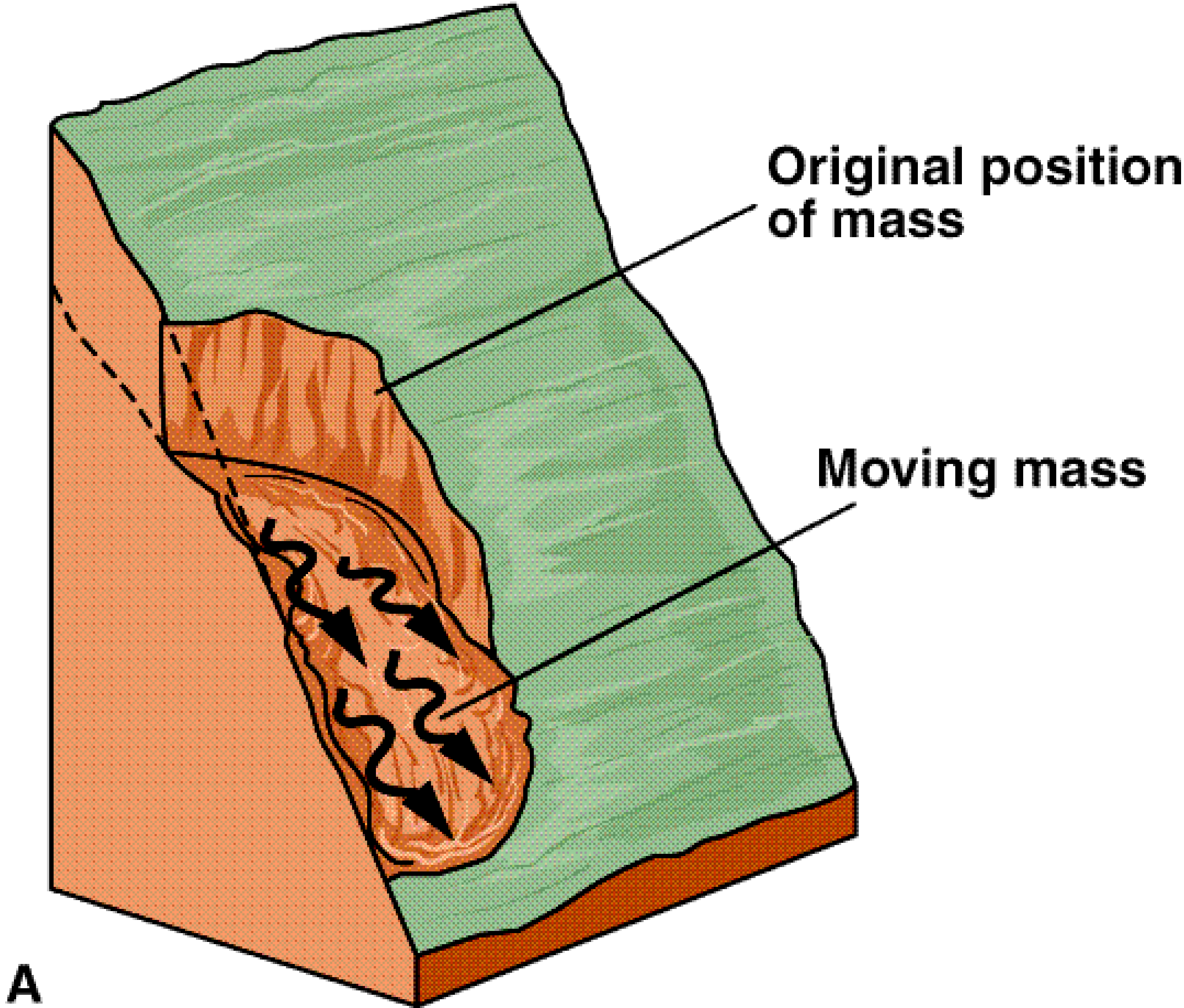
- When a sufficiently large force is applied, any deformable material will begin to flow. In mass-wasting, the force is gravity and the material consists of dense mixtures of sediment and water (or sediment, water, and air).
- Mass-wasting processes that involve the movement of such mixtures are called **flows.**
- The way a sediment flows depends on the relative proportions of solids, water, and air in the mixture and on the physical and chemical properties of the sediment.

Flows

- Top and bottom of material do not flow at same rate.
- Considerable deformation while flowing.
- Slip plane is absent.
- Slow flows are imperceptible.
- Fast flows are visible.

Remember

Flow



Flows

- All streams carry at least some sediment, but if the sediment becomes so concentrated that the water can no longer transport it, a sediment-laden stream becomes a very fluid sediment flow. In such a case the water helps promote flow, but the pull of gravity remains the primary reason for movement.
- In Fig. 6.3 flows are subdivided into **two classes—*slurry flows* and *granular flows***—based on water content (i.e., concentration of sediment).
- ***Slurry flows* *are water saturated mixtures, whereas* *granular flows* *are not water saturated.***
- Each of these two classes is further subdivided on the basis of the velocity of the flow, which can range from very slow (millimeters or centimeters per year) to very fast (kilometers per hour).

Slurry Flows

- **A *slurry flow*** is a moving mass of water-saturated sediment. In slurry flows, the sediment mixture is often so dense that large boulders can be suspended in it.
- Boulders that are too large to remain in suspension may be rolled along by the flow. When the flow ceases, fine and coarse particles remain mixed, resulting in an unsorted sediment.
- Very slow downslope movement of water-saturated soil and regolith is known as ***solifluction***. As can be seen in Fig. 6.3, solifluction lies at the lower end of the velocity scale for flowing sediment—water mixtures.

FIGURE 6.3

- Classification of sediment flows on the basis of their average velocity and sediment concentration.
- The transition from a sediment-laden stream to a slurry flow occurs when the concentration of sediment becomes so high that the stream no longer acts as a transporting agent: instead, gravity becomes the primary force causing the saturated sediment to flow.
- As the percentage of water decreases further, a transition from slurry flow to granular flow takes place. Now the sediment may contain water and/or air.
- The boundaries between muddy streams and slurry flows (A) and between slurry and granular flows (B) are not assigned sediment-concentration percentages because they can shift to the left or right depending on the physical and compositional characteristics of the mixture. Different types of slurry and granular flows are recognized on the basis of their mean velocity.

FIGURE 6.3 Classification of sediment flows

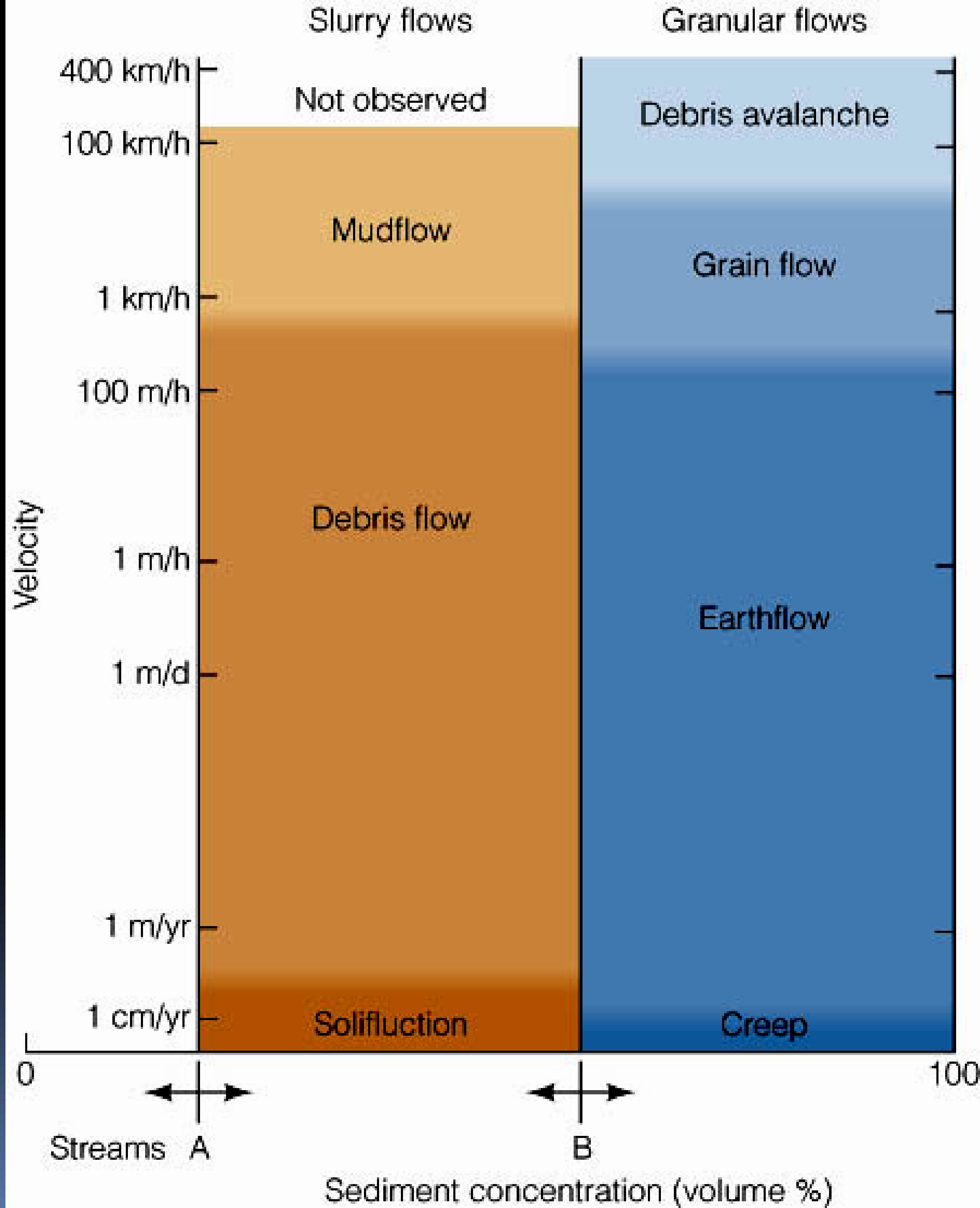
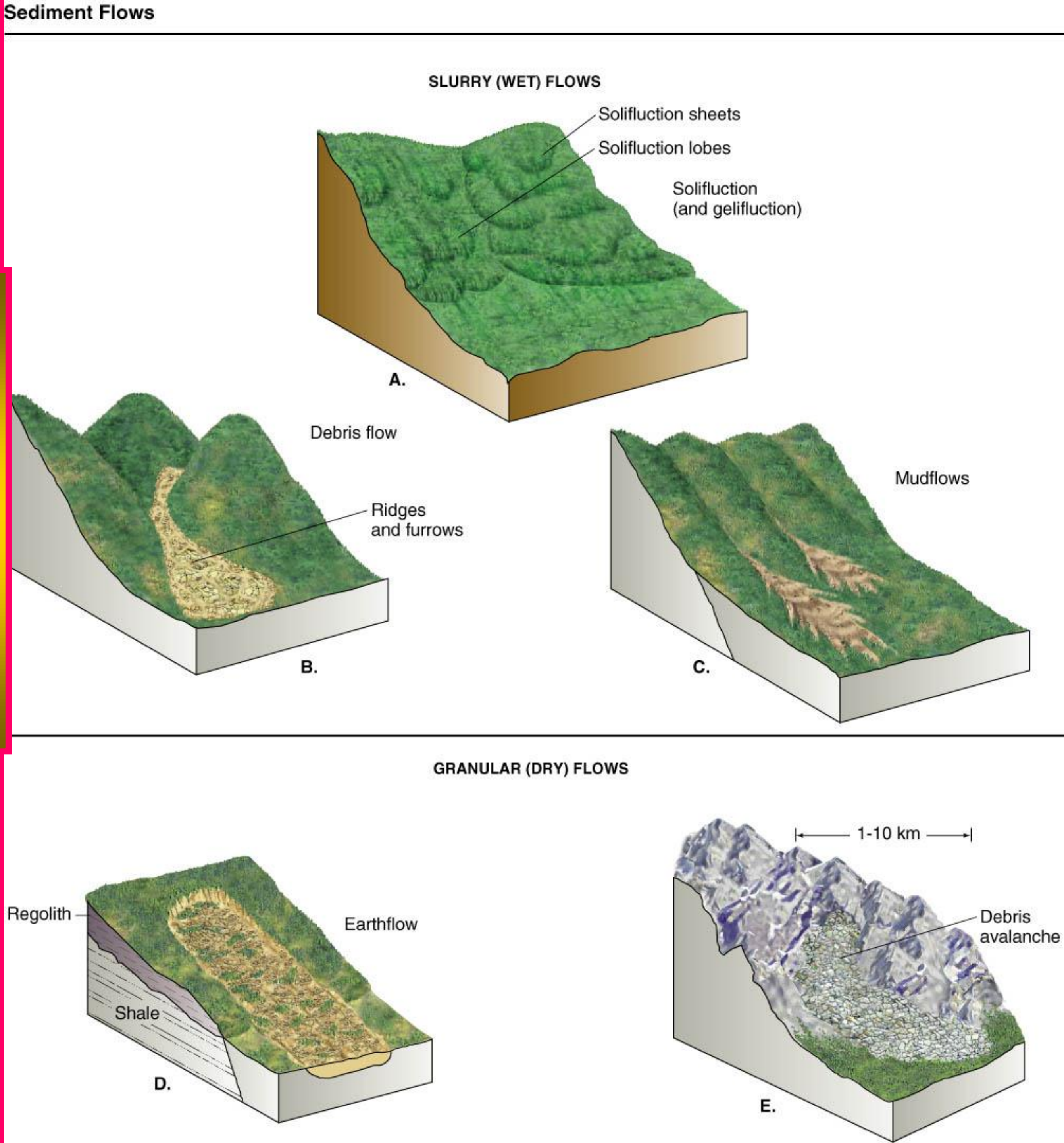


FIGURE 6.4 Examples of slurry flows and granular flows.



Slurry Flows

- The rates of movement of such mixtures are generally so slow as to be detectable only by measurements made over several seasons.
- ***Solifluction*** occurs on hill slopes where sediment remains saturated with water for long intervals. It results in distinctive surface features, including lobes and sheets of debris that sometimes override one another (Figs. 6.4 and 6.5).
- **A *debris flow*** involves the downslope movement of regolith whose consistency is coarser than that of sand, at rates ranging from 1 m/year to as much as 100 m/h (Fig. 6.3). In some cases a debris flow begins with a slump or debris slide, whose lower part then continues to flow downslope (Figs. 6.4). Once mobilized, a typical debris flow moves along a stream channel and may then spread out to form a poorly sorted deposit.

Solifluction

Remember

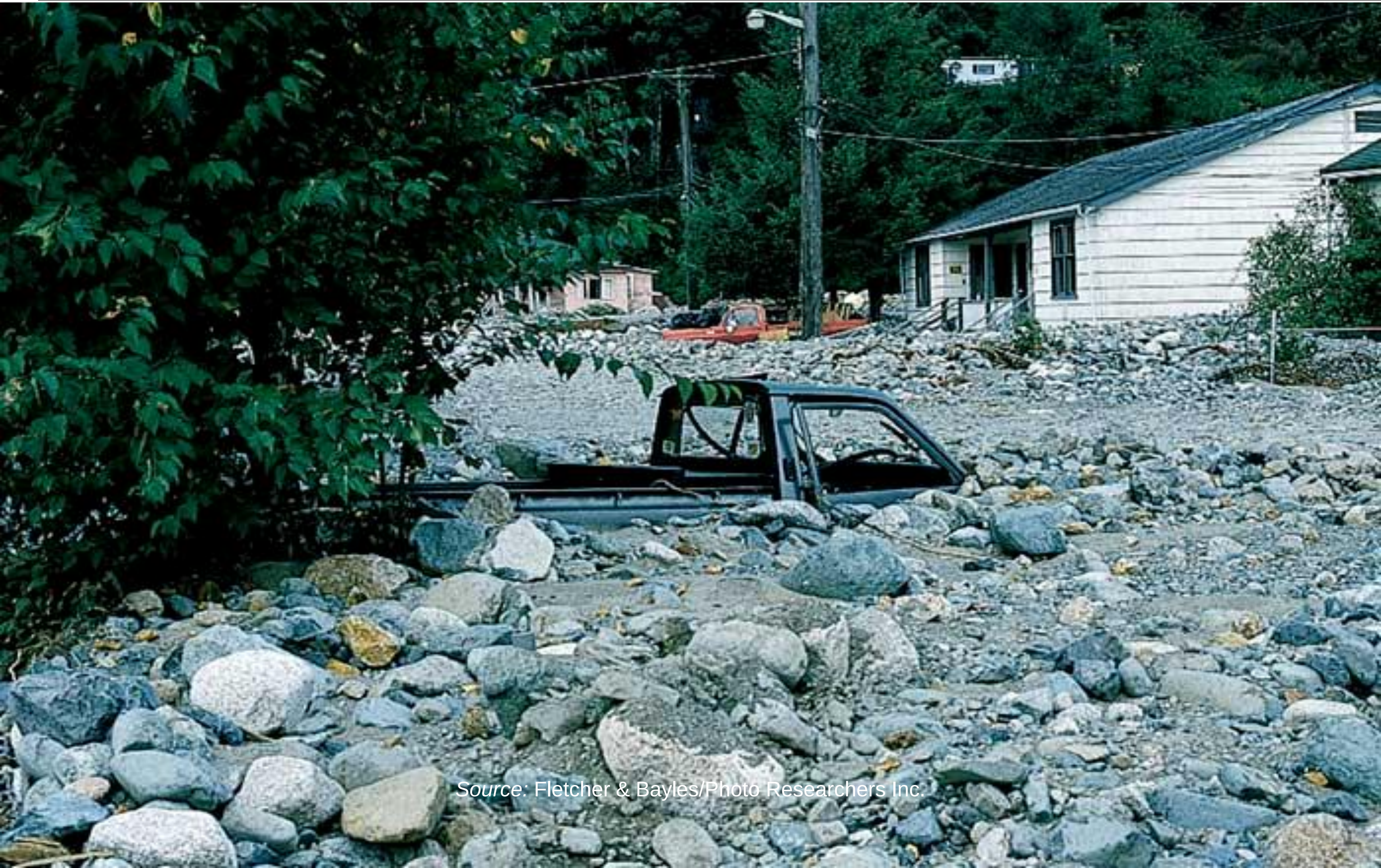
- In permafrost areas.
- In summer, thawed and saturated surface soil and rock debris flow downslope.
- Movement facilitated by lubricated interface between thawed active layer and frozen permafrost.

FIG U R E 6.5 meter-thick solifluction lobe has slowly moved downslope and covers glacial deposits on the floor of the Orgiere Valley in the Italian Alps.

Debris Flow in National Forest Land

Sierra Nevada (CA) debris flow, January, 1997; total length = 4 km.

Debris Flow



Slide Mountain, NV, 1985

This demonstrates that debris flows can carry more than just mud

Debris flow& Mudflow

- ***Debris flow*** deposits commonly have a tongue-like front and a very irregular surface, often with concentric ridges and depressions.
- They are frequently associated with intervals of extremely heavy rainfall that lead to oversaturation of the ground.
- **A debris flow that has a water content sufficient to make it highly fluid is commonly called a *mudflow*.**
- In Fig. 6.3, the velocity of mudflows lies at the upper range of the velocity scale for debris flows (more than about 1 km/h). Most mudflows are highly mobile and tend to travel rapidly along valley floors (Fig. 6.4).

Mudflow

- The consistency of mudflow sediment can range from freshly poured concrete to a souplike mixture only slightly denser than very muddy water.
- After a heavy rain in a mountain canyon, a mudflow can start as a muddy stream that continues to pick up loose sediment until its front becomes a moving dam of mud and rubble, extending to each wall of the canyon and urged along by the force of the flowing water behind it (Fig. 6.7).
- When it reaches open country the moving dam collapses, floodwater pours around and over it, and mud mixed with boulders is spread out in a wide, thin sheet.

Mudflow

Remember

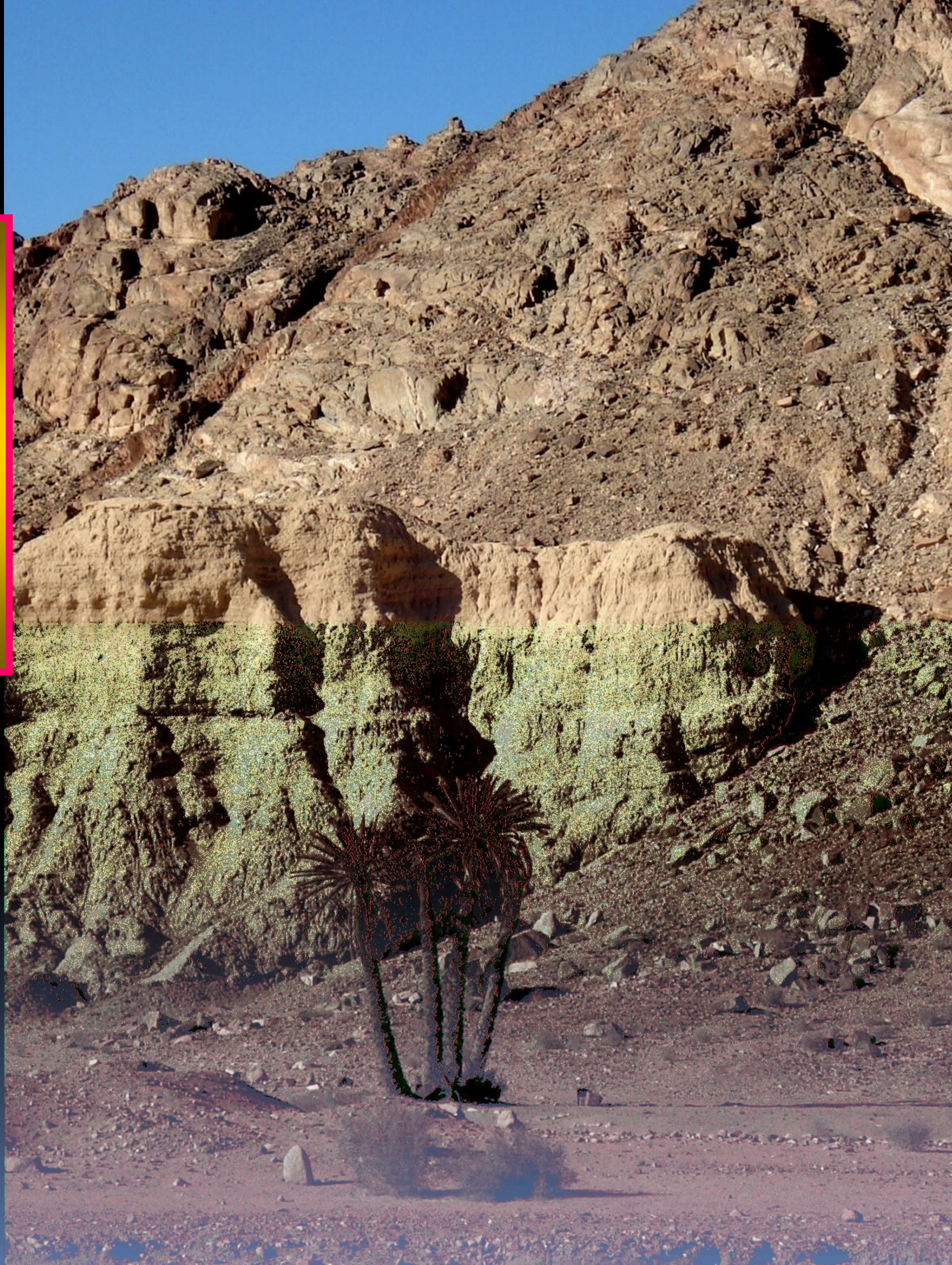
- Type of fast flow.
- Common on steep slopes in arid or semi-arid areas with sparse vegetation and intense rainfall.
- Overland flow entrains unprotected surface sediment.
- Consistency varies.

F I GURE : 6.7:Passage of a muddy debris flow along a canyon near Farmington, Utah, in June 1983. A. The boulder-laden front of a muddy debris flow advances from left to right along a stream channel in the wake of an earlier surge of muddy debris.

B. The steep front, about 2 m high and advancing at 1.3 m/s, acts as a moving dam, holding back the flow of muddy sediment upstream.

C. The main slurry, having a sediment concentration of about 80 percent and now moving at about 3 m/s, is thick enough to carry cobbles and boulders in suspension.

Lithified Mudflow Deposits Southern Sinai



Lithified Mudflow Deposits
Southern Sinai

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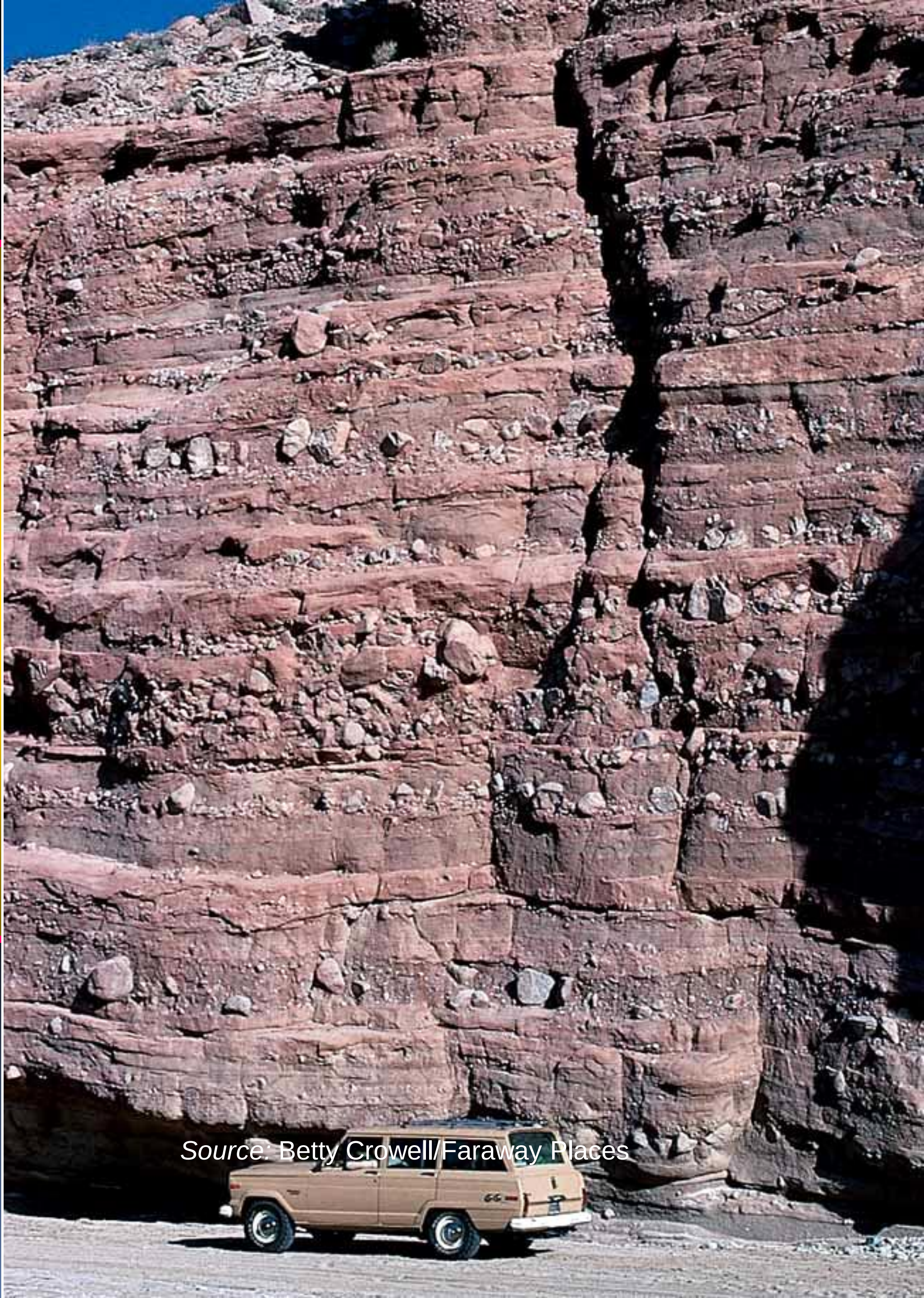
Southern Sinai

Lithified Mudflow Deposits



Source: Betty Crowell/Faraway Places

Mudflow

- Throughout much of its history Mount St. Helens has produced mudflows, the most recent of which occurred during the huge eruption of May 1980 (Fig. 6.8).
- On active volcanoes in wet climates, layers of tephra and volcanic debris commonly cover the surface and are easily mobilized as mudflows called ***lahars***.
- When closely associated with an actual eruption, lahars can be very hot.

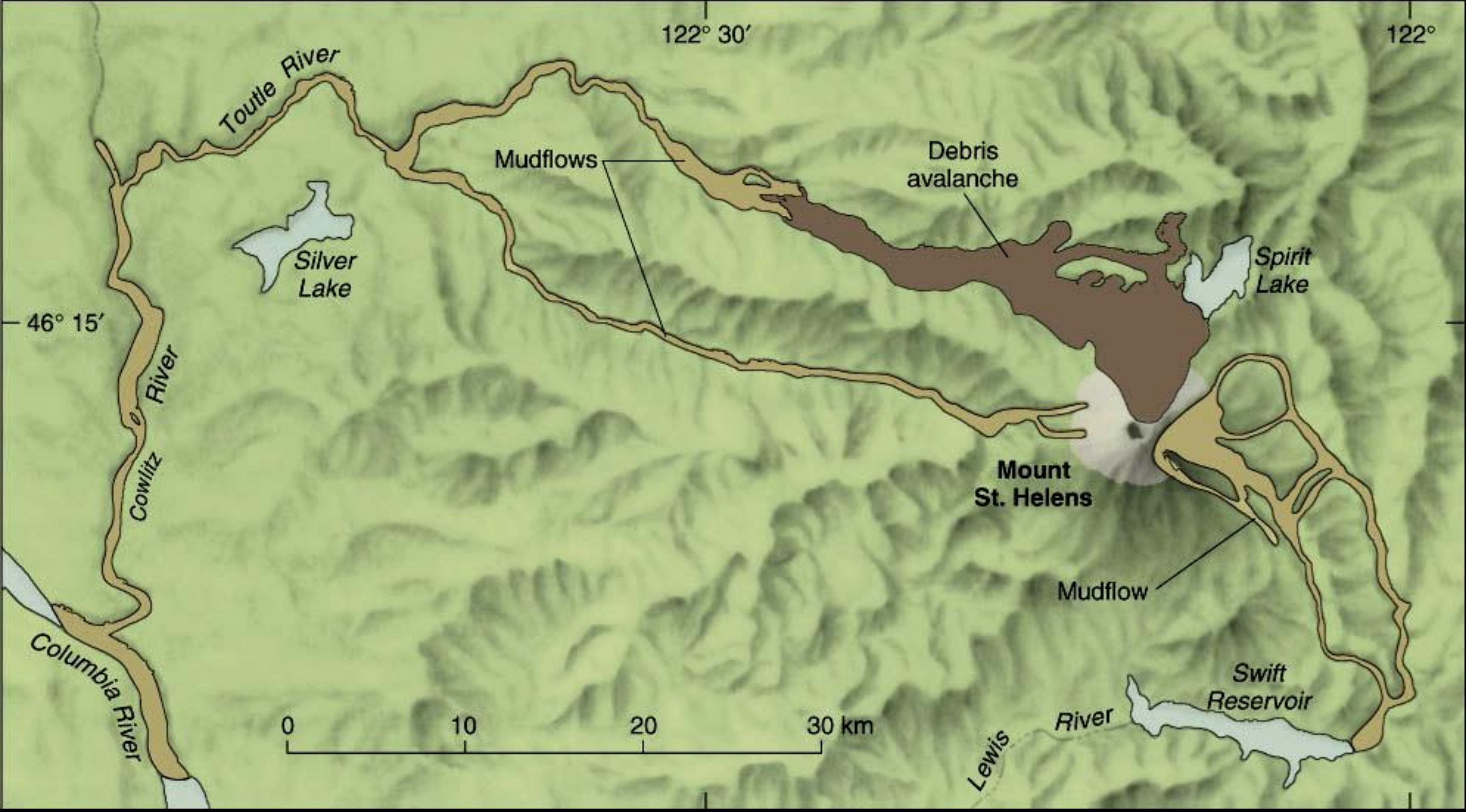


FIGURE 6.8: During the 1980 eruption of Mount St. Helens in Washington, volcanic mudflows were channeled down valleys west and east of the mountain. Some mudflows reached the Columbia River after traveling more than 90 km. Flow velocities were as high as 40 m/s and averaged 7 m/s.

Granular Flows

- ***A granular flow*** is a mixture of sediment, air, and water but, unlike a slurry flow, it is not saturated with water; instead, the weight of the flowing sediment is supported by contact or collision between grains. The sediment of granular flows may be largely dry, with air filling the pores, or it may contain water but include a range of grain sizes and shapes that allows the water to escape easily.
- ***Creep*** is an imperceptibly slow granular flow. Most of us have seen evidence of creep in curved tree trunks or old fences, telephone poles, or gravestones leaning at an angle on hill slopes (Fig. 6.9). Steeply inclined rock layers may be bent over in the downslope direction just below the surface of the ground, another sign of creep.

Indicators of Creep

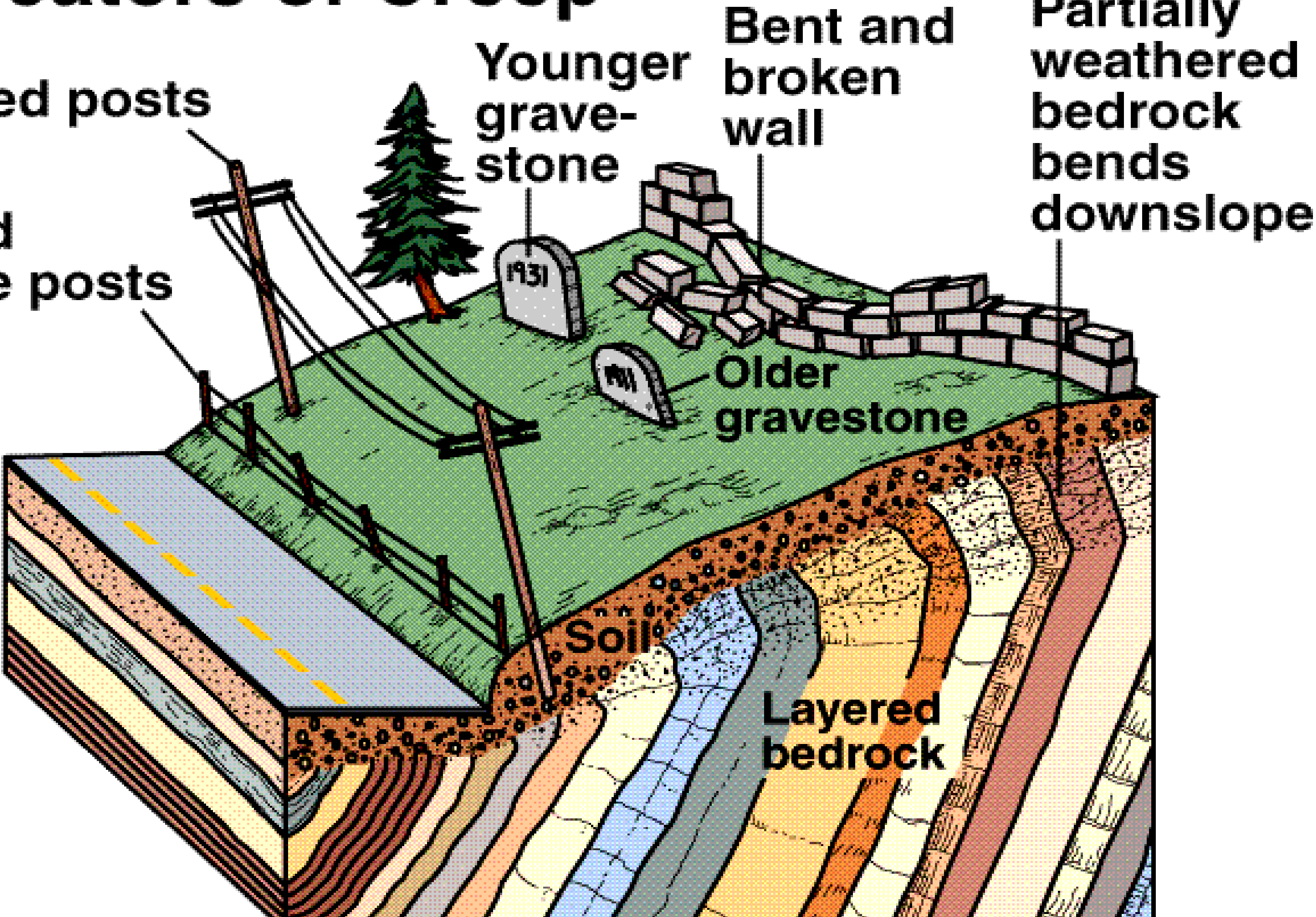


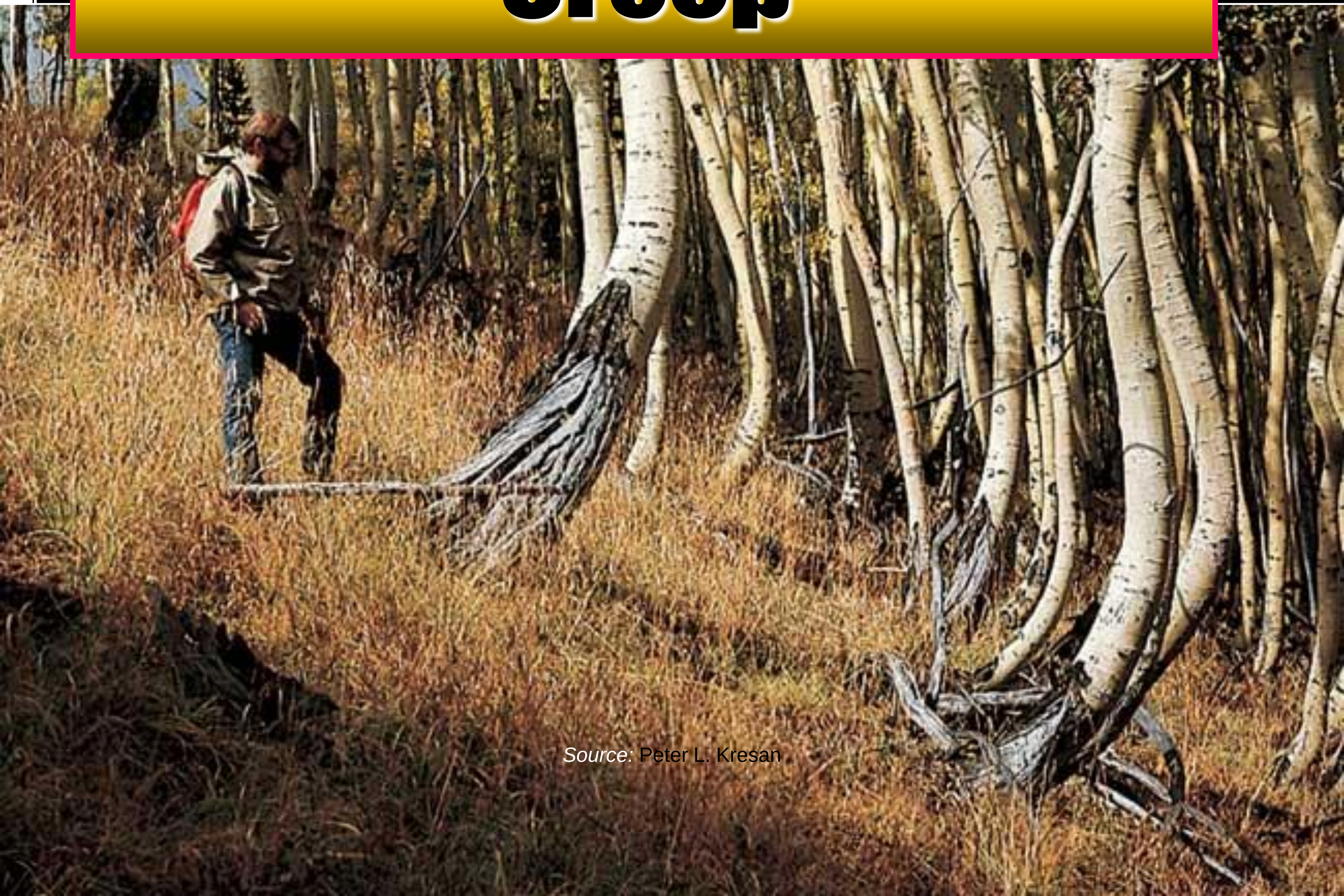
FIGURE 6.9: Effects of creep on surface features and bedrock


creep

Creep

- A number of factors contribute to creep, including the growth and decay of plants (which can bind sediment particles together or wedge them apart); the activities of animals (such as burrowing or trampling); and heating, cooling, wetting, and drying (all of which cause changes in the volume of mineral particles).
- However, as with all types of mass-wasting, gravity is the main downslope force.

Creep



Source: Peter L. Kresan

Creep

- As might be expected, rates of creep tend to be higher on steep slopes than on gentle slopes. Measurements in Colorado, for example, document a creep rate of 9.5 mm/year on a slope of 39° but a rate of only 1.5 mm/year on a 19° slope.
- Creep races also tend to increase as the amount of moisture in the soil increases. However, in wet climates the density of vegetation also increases, and roots, which bind the soil together, tend to inhibit creep.

Earthflows

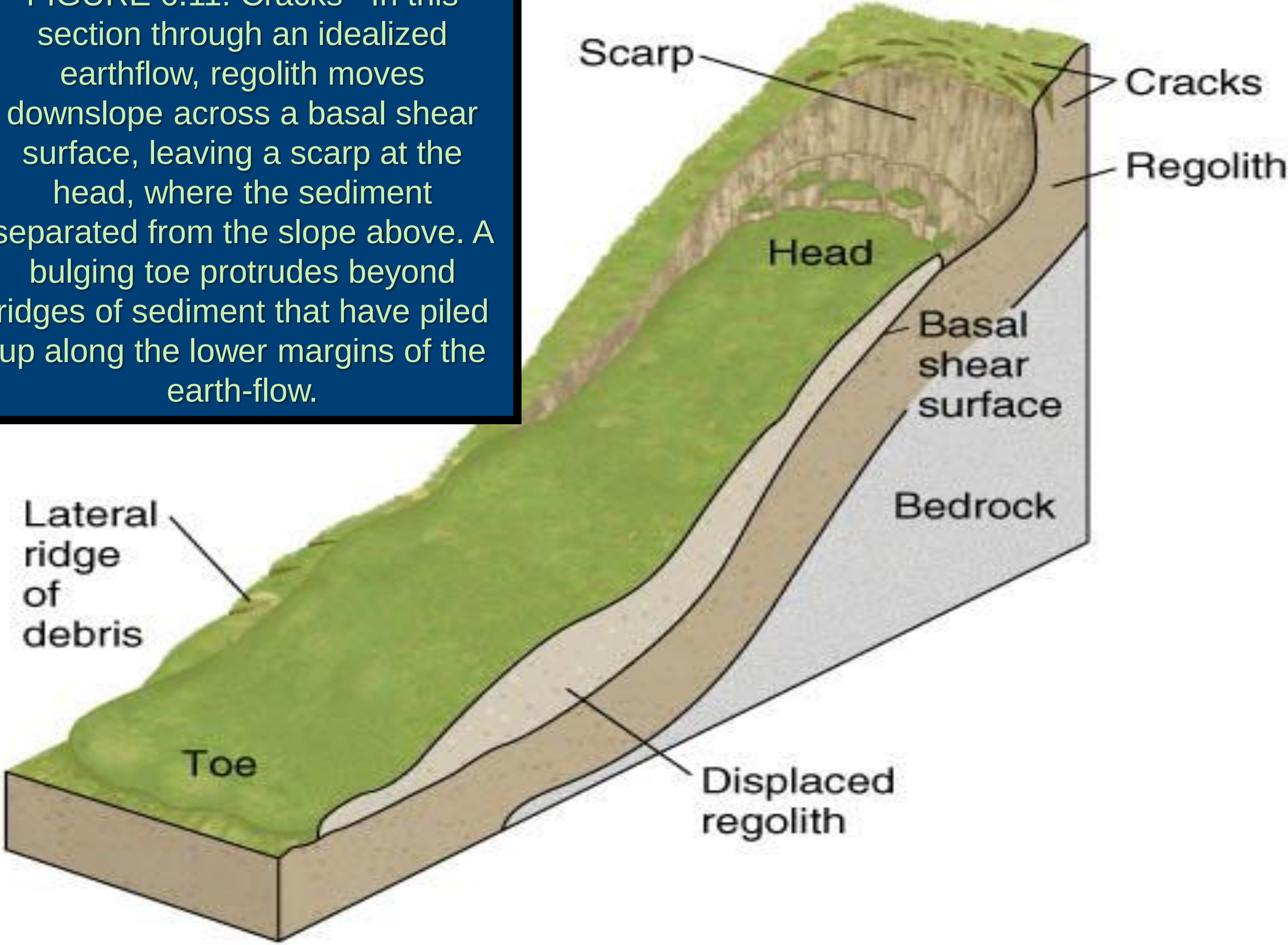
- **Earthflows** are among the more common types of mass-wasting. An earthflow is a downslope granular flow that is more rapid than creep (Fig. 6.3).
- Earthflows may continue for several days, months, or even years. Even after their initial motion ceases, they may be highly susceptible to renewed movement.
- Earthflows occur where the ground is saturated intermittently, and they are frequently associated with intervals of excessive rainfall.
- An earthflow typically heads in a steep **scarp,** a cliff that is formed where displaced material has moved away from undisturbed ground upslope (Fig. 6.11).

Earthflow

Remember

- Type of fast flow.
- Mass of water-saturated soil or regolith moves downslope.
- Commonly occurs where bedrock is dominated by clay.

FIGURE 6.11: Cracks In this section through an idealized earthflow, regolith moves downslope across a basal shear surface, leaving a scarp at the head, where the sediment separated from the slope above. A bulging toe protrudes beyond ridges of sediment that have piled up along the lower margins of the earth-flow.



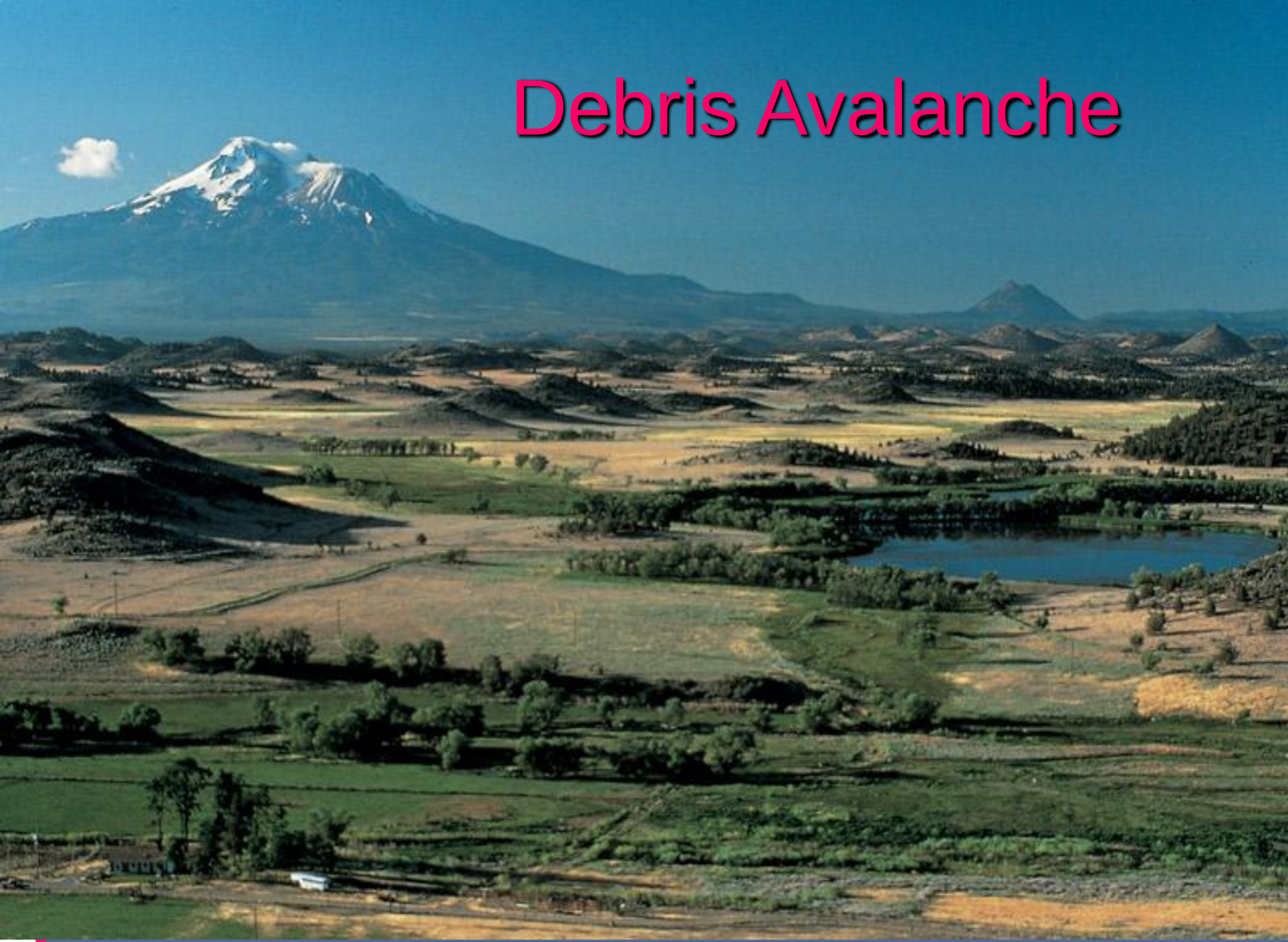
Grain Flow

- If you have ever walked along the crest of a sand dune and stepped too close to the steep slope that faces away from the wind, your footsteps likely started a cascade of sand flowing down the dune face.
- This is an example of still another type of mass-wasting, called ***grain flow***, <u>which involves the movement of a dry or nearly dry granular sediment with air filling the pore spaces.</u>

Debris Avalanche

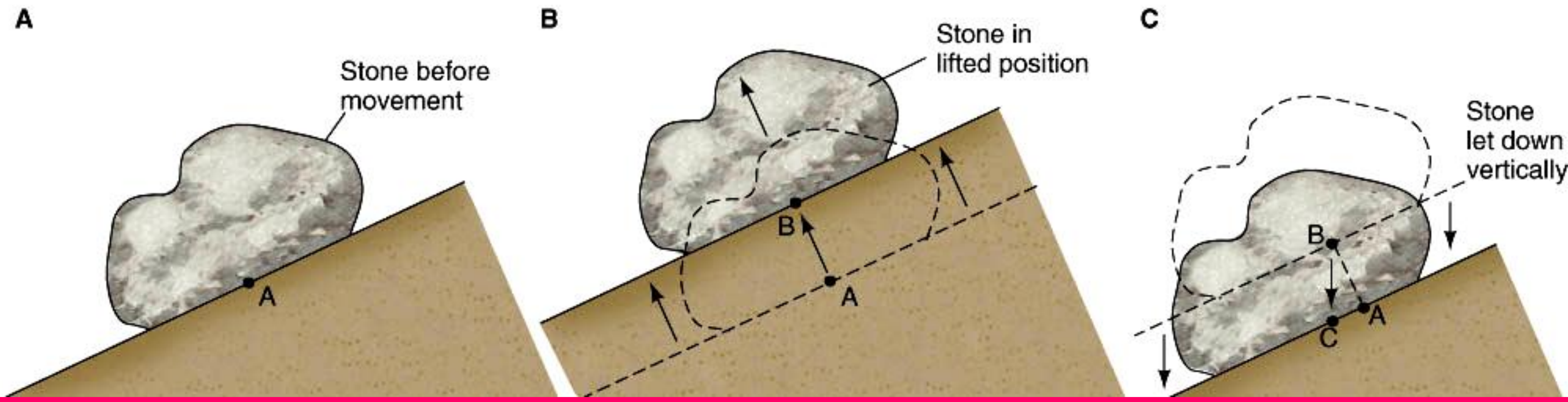
- **A *debris avalanche*** is a type of granular flow that travels at high velocity (tens to hundreds of kilometers per hour) and can be extremely destructive (Fig. 6.4). Large debris avalanches are rare but spectacular events involving huge masses of falling rock and debris that break up, pulverize on impact, and then continue to travel downslope, often for great distances.
- It has been suggested that the debris actually rides on a layer of compressed air. If this is true, debris avalanches behave somewhat like a commercial hovercraft that travels across land or water on air compressed by a large propeller.
- The slopes of steep, unstable stratovolcanoes are especially susceptible to collapse, leading to the production of debris avalanches.

Debris Avalanche



Mass-Wasting in Cold Climates

- Mass-wasting is especially prevalent at high latitudes and high altitudes, where average temperatures are very low. In such regions much of the landscape is underlain by perennially frozen ground, and frost action is an important geologic process. When water freezes, its volume increases. Ice forming in saturated regolith therefore pushes up the ground surface in a process called **frost heaving**.
- Frost heaving strongly influences the downslope creep of sediment in cold climate.


A
Stone before
movement
A
B
Stone in
lifted position
B
A
C
Stone
let down
vertically
B
A
C

Mass-Wasting in Cold Climates

- In cold regions that are underlain by frozen ground year round, a thin surface layer thaws in summer and refreezes in winter. During the summer the thawed layer becomes saturated with meltwater and is very unstable, especially on hillsides. As gravity pulls the thawed sediment slowly downslope, distinctive lobes and sheets of debris are produced.
- This process, which is similar to solifluction in temperate and tropical climates, is known as ***gelifluction.***
- Although measured rates of movement are generally less than 10 cm/year, gelifluction is so widespread on high-latitude landscapes.

Rock Glacier

- ***A rock glacier***, another characteristic feature of many cold, relatively dry mountain regions, is a tongue or lobe of ice-cemented rock debris that moves slowly downslope in a manner similar to the movement of a glacier (Fig. 6.12).
- Rock glaciers generally originate below steep cliffs, which provide a source of rock debris. Active rock glaciers may reach a thickness of 50 m or more and advance at rates of up to about 5 m/year. They are especially common in high interior mountain ranges such as the Swiss Alps, the Argentine Andes, and the Rocky Mountains.

Rock Glacier

Subaqueous Mass-Wasting

- As geologists have extended the search for petroleum to off-shore regions, their explorations have shown that mass-wasting is an extremely common and widespread means of sediment transport on the sea floor. Mass-wasting also has been documented in lakes.
- Extensive studies of the offshore slopes of eastern North America have shown that vast areas of the sea floor are disrupted by submarine slumps, slides, and flows.
- A subaqueous slope failure can give rise to a ***turbidity current***, a type of sediment flow that travels down submarine canyons and deposits sediments off the continental shelf. Major marine deltas also frequently display surface features and sediments that can be attributed to slope failures.

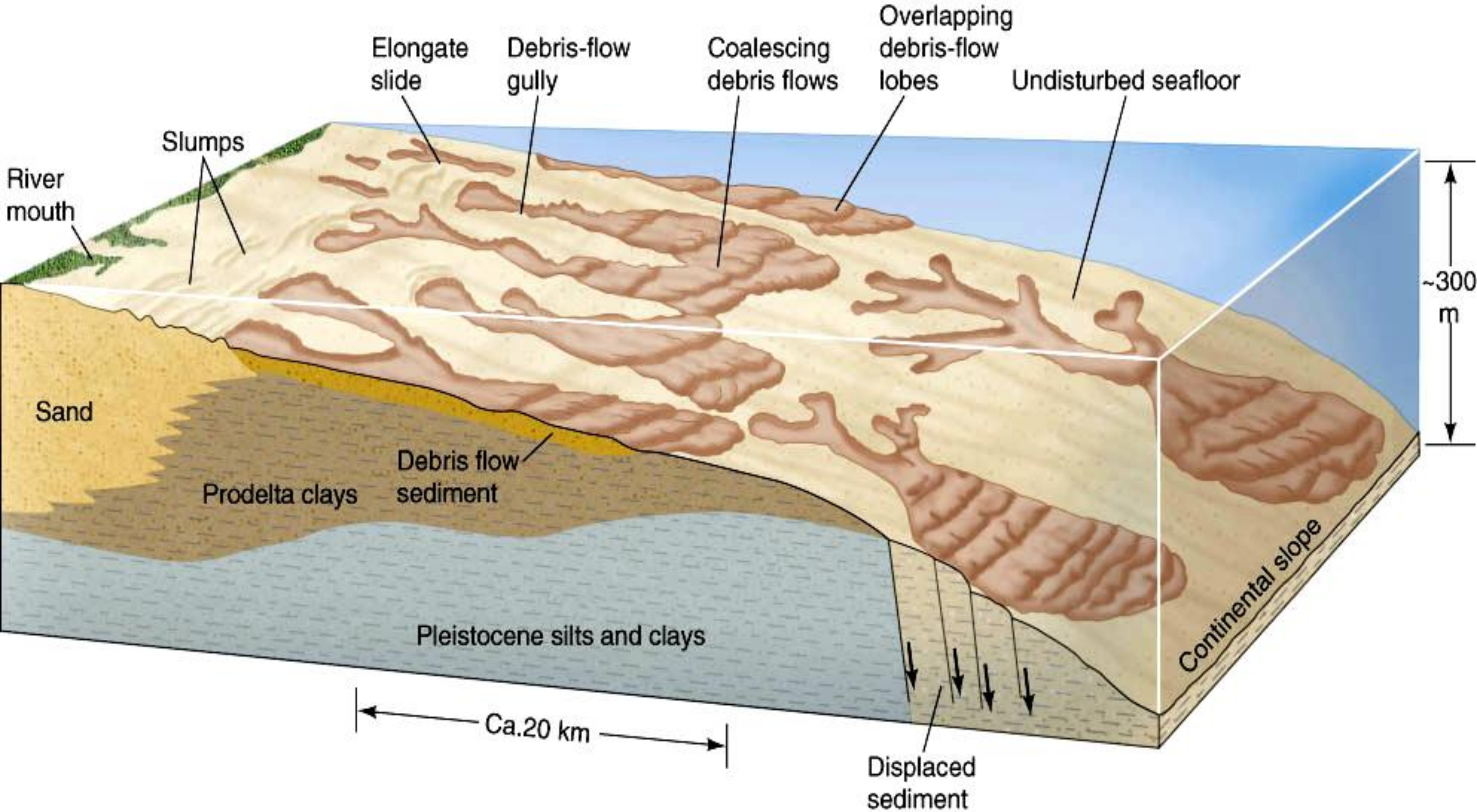


FIGURE 6.13: Block diagram showing various mass-wasting features on the submarine surface of the Mississippi Delta.

FACTORS THAT INFLUENCE SLOPE STABILITY

- Under natural conditions, a slope evolves toward an angle that allows the quantity of regolith reaching any point from upslope to be balanced by the quantity that is moving downslope from that point. Such a slope is said to be in a balanced, or ***steady-state***, condition.
- Many factors affect slope stability. A change in any one or a combination of these factors can alter the steady-state condition of the slope, decreasing its stability and sometimes leading to slope failure. In some cases, the change may take the form of a relatively sudden triggering event, whether natural (such as an earthquake) or human-generated (such as an explosion).

Factors That Influence Slope Stability

- In other cases, the slope may have been slowly changing over time; again, the cause can be natural (such as a long period of intense precipitation) or a result of human activities (such as the construction of a dam).
- The main factors that influence slope stability are
- (1) **the force of gravity**, and therefore the gradient of the slope;
- (2) **water**, and therefore the hydrologic characteristics of the slope;
- (3) **the presence of troublesome Earth materials**; and
- (4) **the occurrence of a triggering event**.

FACTORS THAT INFLUENCE SLOPE STABILITY

- (1) **The force of gravity**
- (2) **Water**
- (3) **The presence of troublesome Earth materials**
- (4) **The occurrence of a triggering event.**

Remember

(1) Gravity and Slope Gradient

- Two opposing forces determine whether a body of rock or debris located on a slope will move or remain stationary.
- **These forces are shear stress and shear strength.**
- **Shear stress, causes movement of the body parallel to the slope.**
- The primary factor influencing shear stress is the pull of gravity, which is related to the slope's **gradient**, or steepness. On a horizontal surface, gravity holds objects in place by pulling on them in a direction perpendicular to the surface (Fig. 6.14).

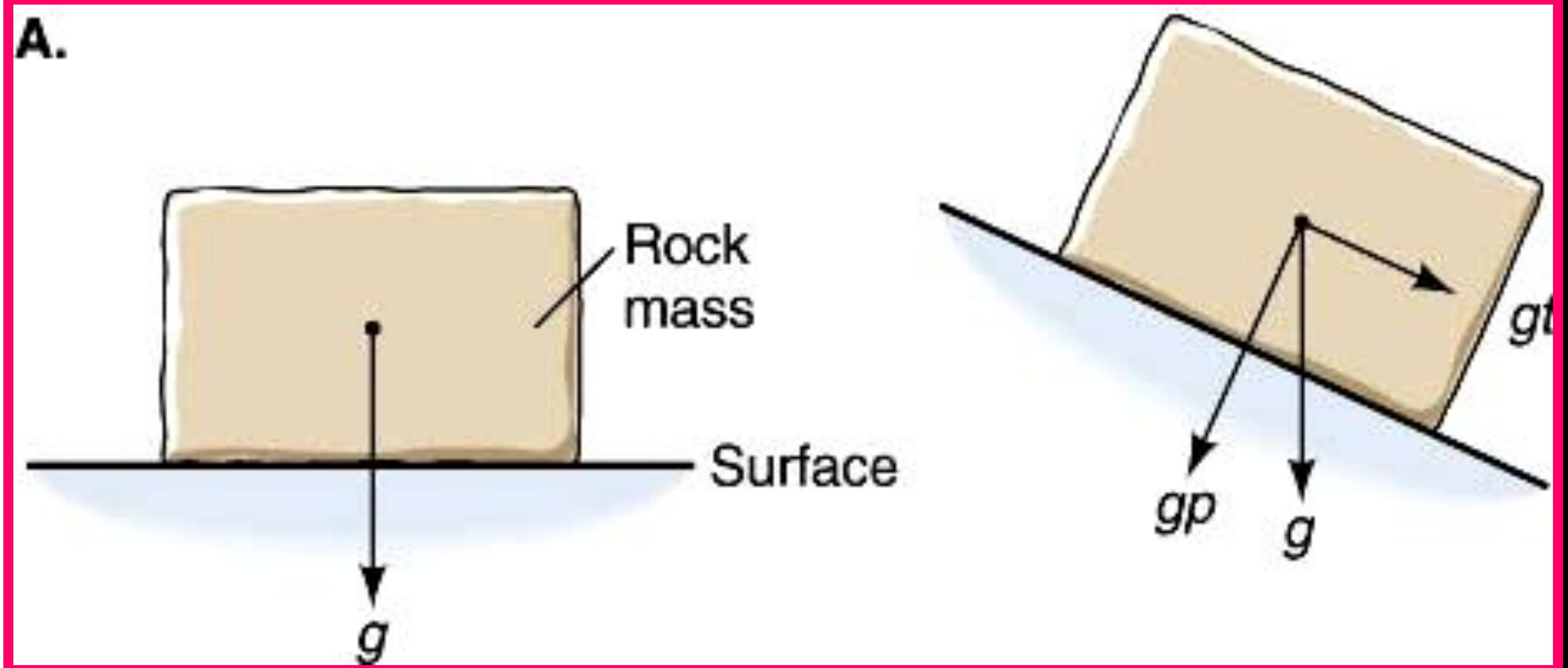
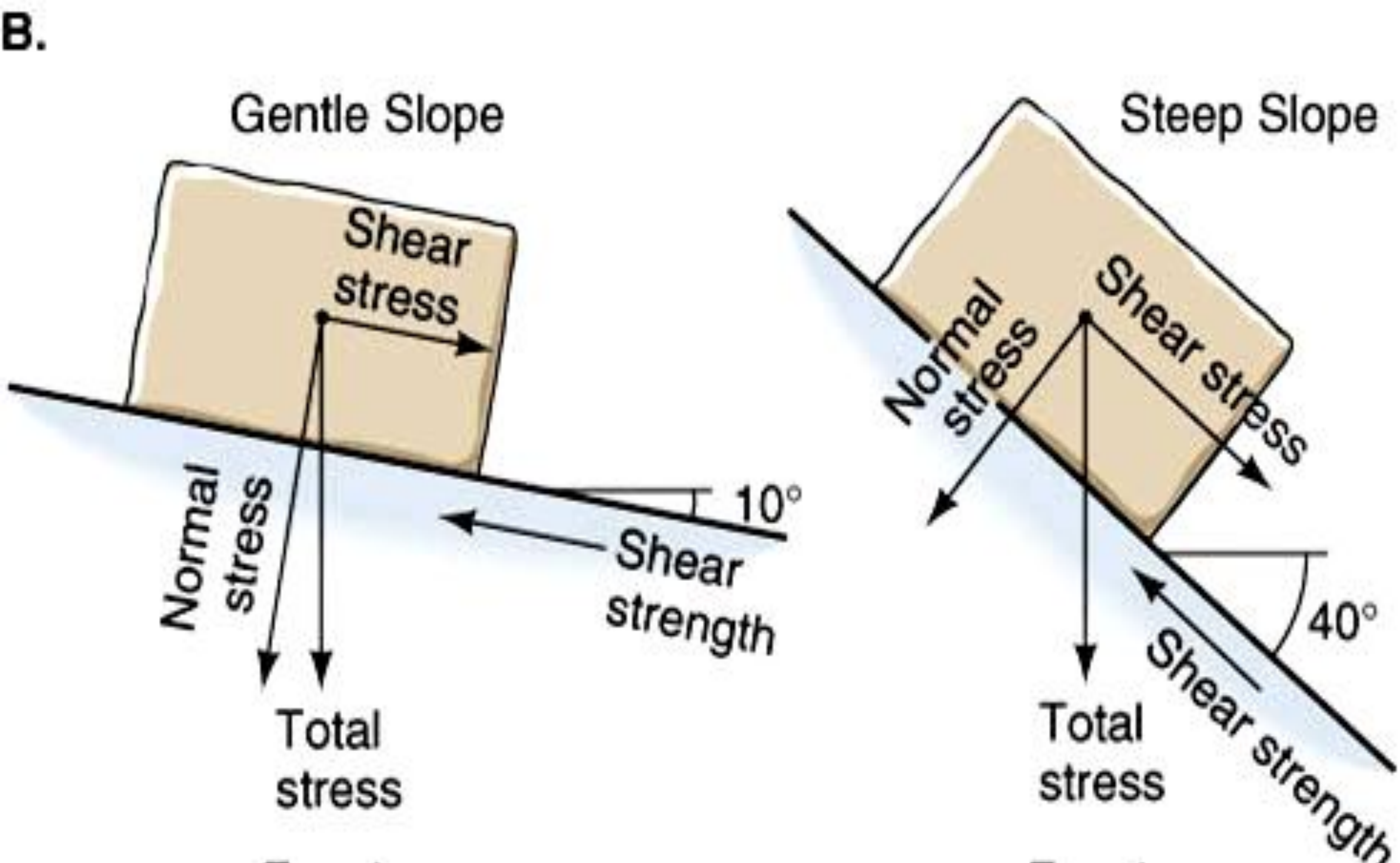


FIGURE 6.14: Effects of gravity on a rock lying on a hillslope. Gravity acts vertically and can be resolved into two components, one perpendicular (gp and the other parallel (gt) to the surface.



Fs > 1
Rockmass Stable

Fs < 1
Failure occurs

(1) Gravity and Slope Gradient

- On any slope, however, gravity consists of two component forces.
- The **perpendicular** component (gp in Fig. 6.14) acts at right angles to the slope and tends to hold objects in place.
- The **tangential** component (g in Fig. 6.14) acts along and down the slope and causes objects to move downhill.

(1) Gravity and Slope Gradient

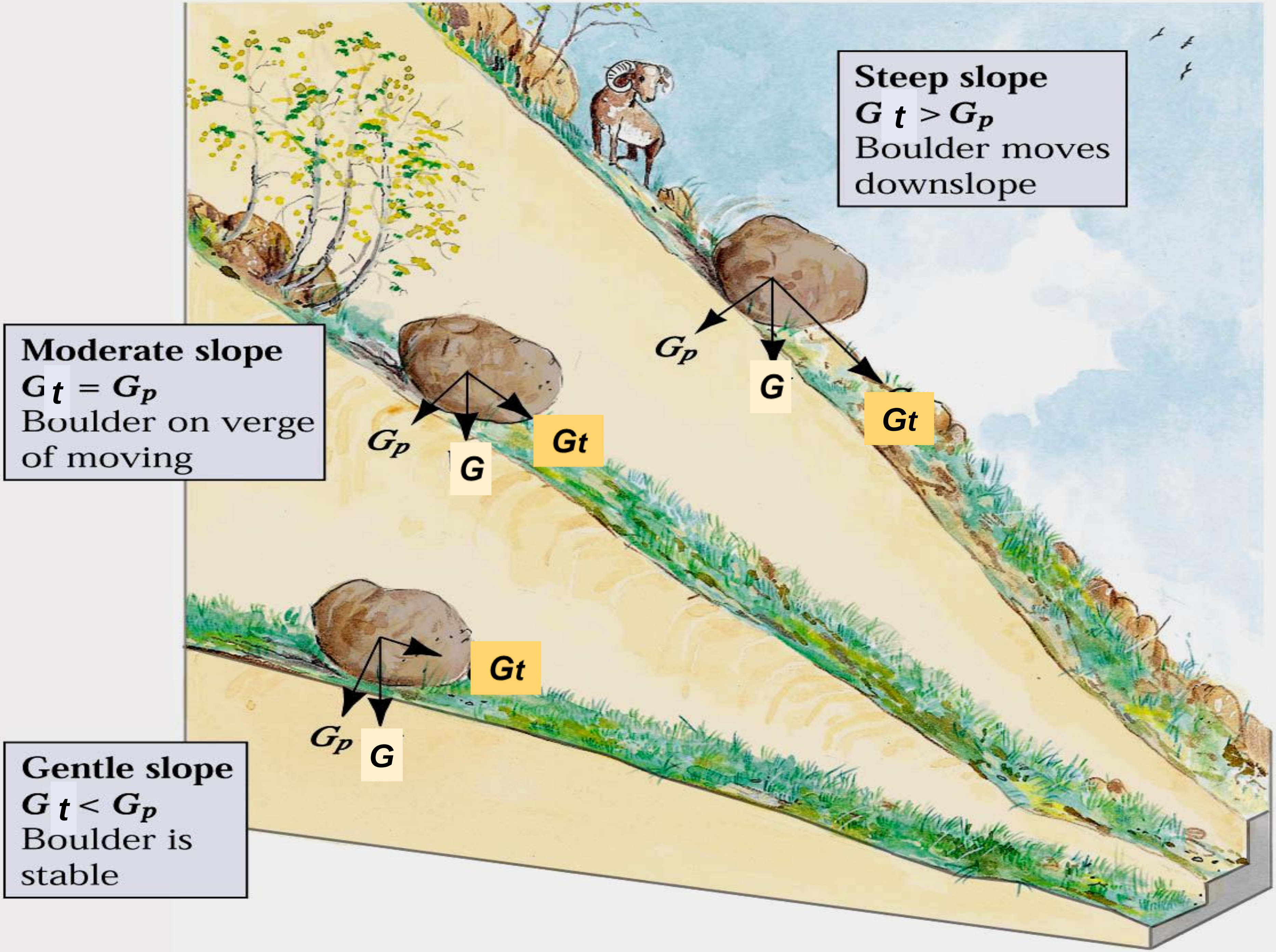
- As a slope becomes steeper, the tangential component increases relative to the perpendicular component and the shear stress becomes larger.
- The second force, **shear strength**, is the internal resistance of the body to movement.
- Shear strength is governed by factors inherent in the body of rock or regolith, such as friction and cohesion between particles and the binding action of plant roots. As long as shear strength exceeds shear stress, the rock or debris will not move.

(1) Gravity and Slope Gradient

- However, as these two forces approach a balance, the likelihood of movement increases. This relationship is expressed in a ratio known as the **safety factor** (denoted
- **Fs = $\dfrac{\text{shear strength}}{\text{shear stress}}$**
- When the safety factor is less than 1 (i.e., shear strength is less than shear stress), slope failure is imminent.

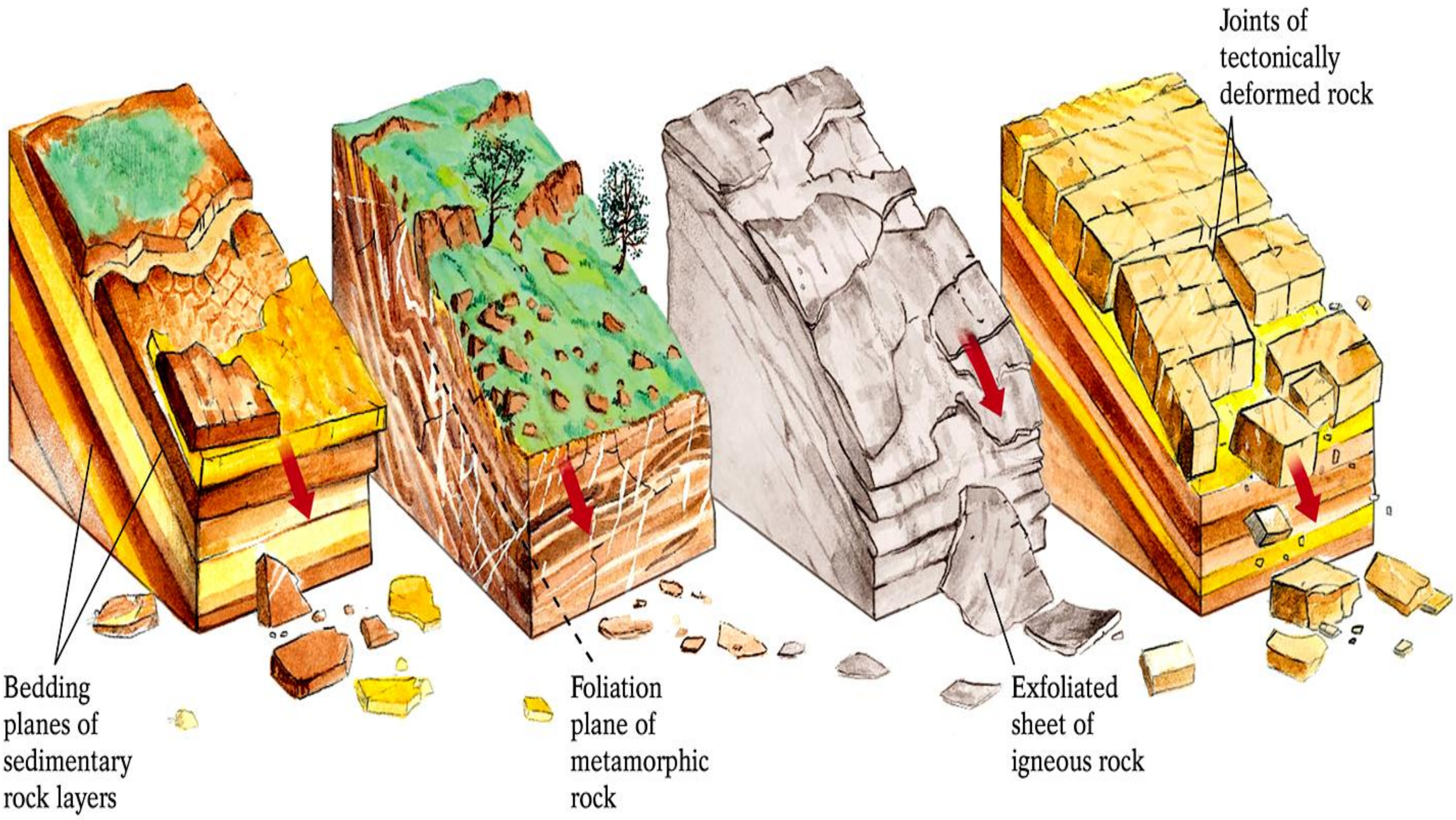
(1) Gravity and Slope Gradient

- The relationship between shear stress and slope gradient (the steeper the slope, the greater the shear stress) means that conditions favoring *mass movement tend to increase as slope angle increases.*
- Steep slopes, of course, are most common in mountainous areas, so it is not surprising that mass-wasting is most frequent in high mountains.



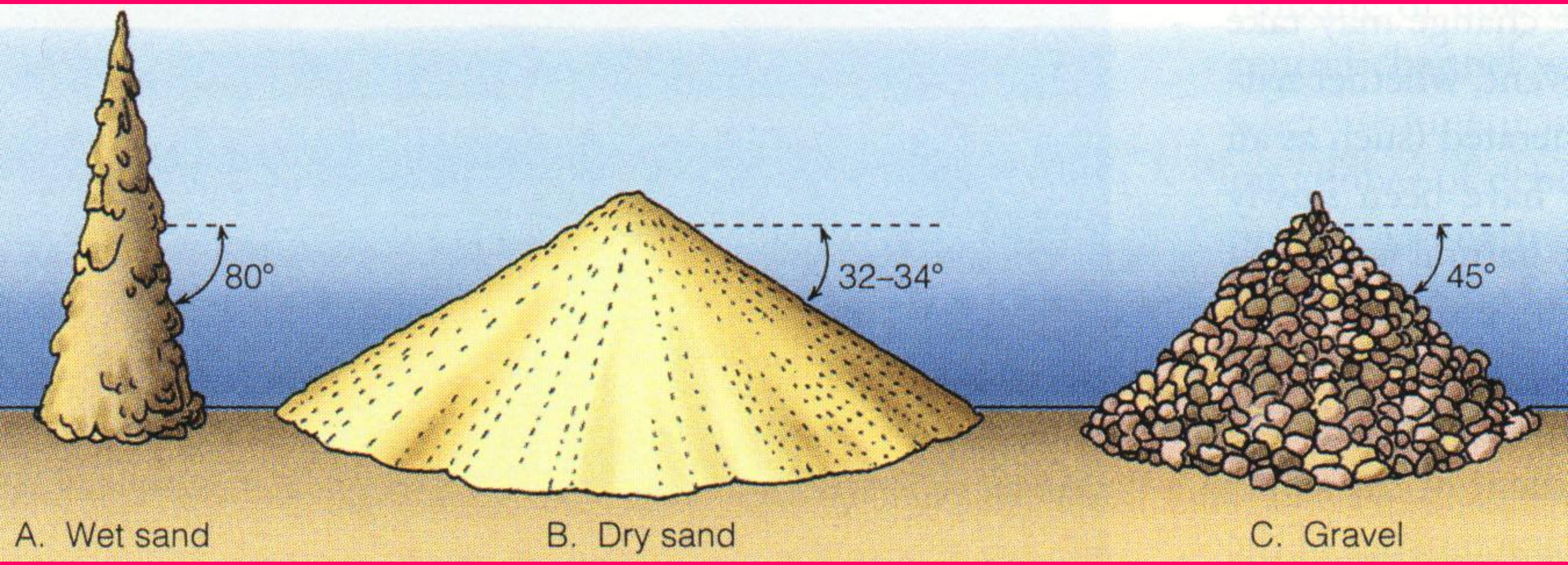
Steep slope
$G_t > G_p$
Boulder moves downslope
G_p
G
G_t
Moderate slope
$G_t = G_p$
Boulder on verge of moving
G_p
G
G_t
G_t
G_p
G
Gentle slope
$G_t < G_p$
Boulder is stable

Slopes susceptible to mass movement.



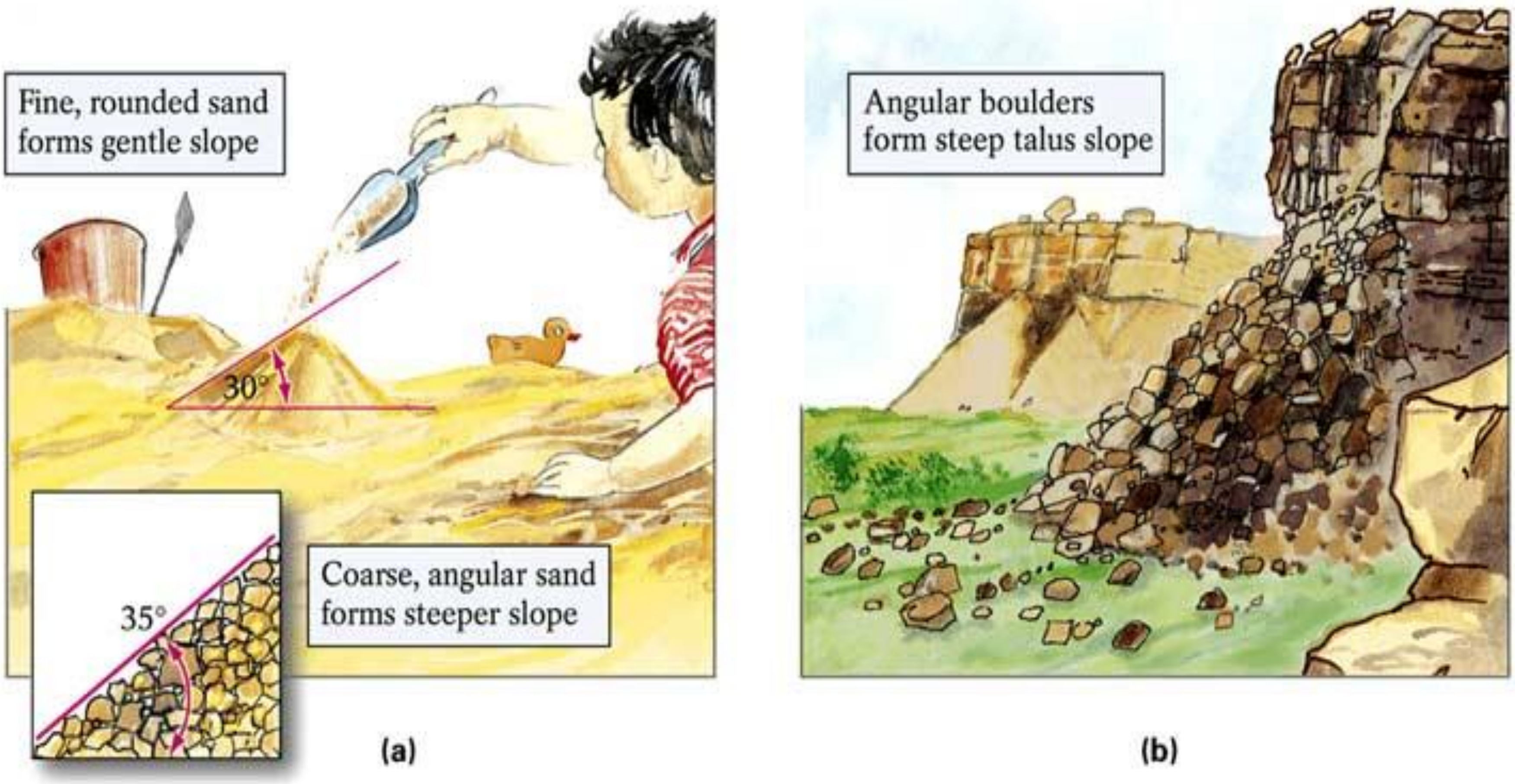
(2) Water

- Water is almost always present within rocks and regolith near the Earth's surface, and it plays a variety of important roles in mass-wasting of both solid rock and regolith. Unconsolidated (loose, uncemented) sediments behave in different ways depending on whether they are dry or wet, as anyone knows who has constructed a sand castle at the beach.
- Dry sand is unstable and difficult or impossible to mold. When poured from a bucket, dry sand (or any other dry, unconsolidated sediment) will form a cone-shaped mound.
- The steepness of the cone's sides, called the **angle of repose**, is determined by the characteristics of the material, primarily the size and angularity of the particles. Sand, for example, will always pile up with slopes of about 32° to 34° (Fig. 6.15).



F 1 G U R E 6.15: Angle of repose in unconsolidated materials. A. Wet sand can be piled up steeply, but (B) dry sand will always come to rest in a cone-shaped mound with slopes of about 32° to 34°. If more sand is poured onto the pile, it will simply roll down the slopes. C. Coarser material, such as gravel, will have a steeper angle of repose. Moisture content and the angularity of particles can also affect a material's angle of repose.

Angle of Repose/Particle Size and Shape



(2) Water

- When a little water is added, the sand gains strength; its angle of repose is greater, so it can be shaped into vertical walls.
- The water and sand grains are drawn together by **surface tension**, a property of liquids that causes the exposed surface to contract to the smallest possible area.
- This force tends to hold the wet sand together as a cohesive mass. However, the addition of *too* much water saturates the sand; the spaces fill with water, and the sand grains lose contact with one another. The mixture turns into a slurry that easily flows away.

(2) Water

- Moist or weakly cemented fine-grained sediments, such as fine silt and clay, may be so cohesive that they can stand in near-vertical cliffs.
- But if the silt or clay becomes saturated with water and the internal fluid pressure rises, the fine-grained sediment may also become unstable and begin to flow like the water-saturated sand castle.
- The movement of some large masses of rock has been attributed to water pressure in voids in the rock.

(2) Water

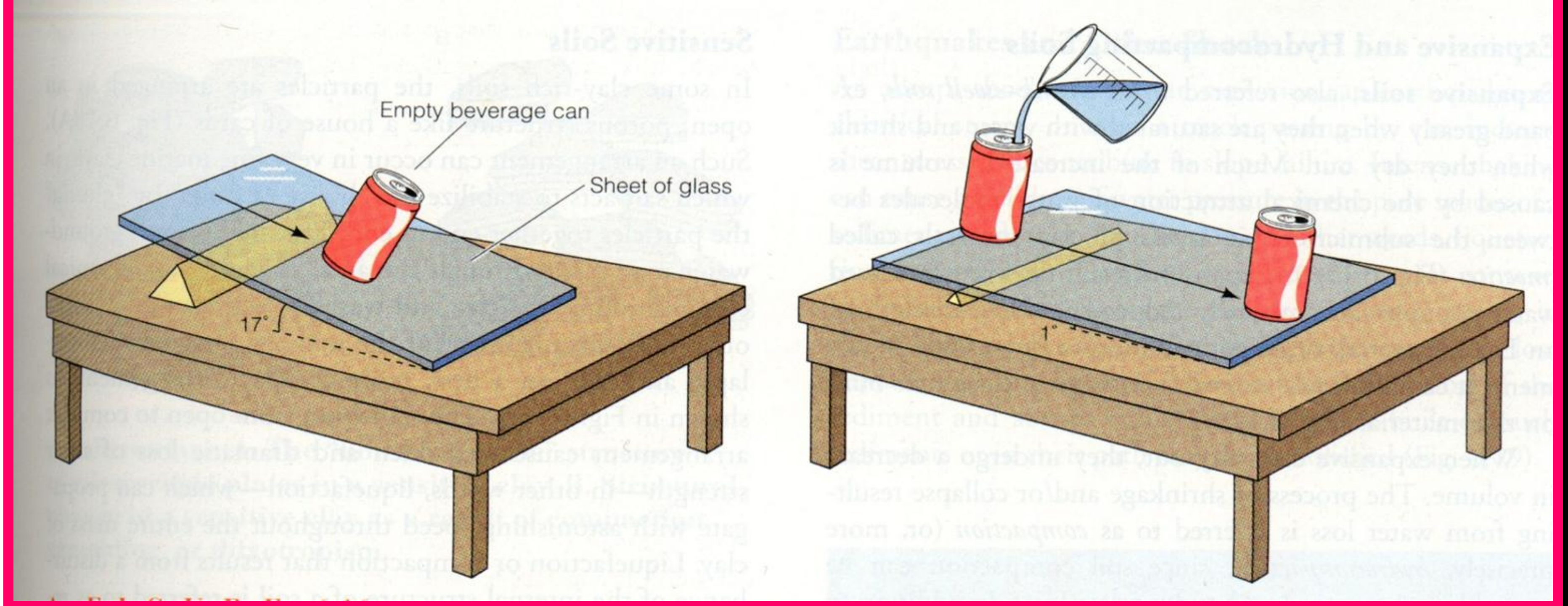
- If the voids along a surface separating two rock masses are filled with water, and the water is under pressure, a buoying effect may result.
- In other words, the water pressure may be high enough to support the weight of the overlying rock mass, thereby reducing friction along the points of contact.
- The result can be a sudden failure. An analogous situation can make driving in a heavy rainstorm extremely dangerous.

(2) Water

- When water is compressed beneath the wheels of a moving car, the increasing fluid pressure can cause the tires to "float" off the roadway, a condition known as hydroplaning.
- You can demonstrate this principle by conducting a simple experiment (a variation on a classic experiment first described by geologists M. King Hubbert and William Rubey in 1959).
- An empty beverage can is placed in an upright position on the wetted surface of a sheet of glass (Fig. 6.16A). If the glass is slowly tilted, the can will not begin to slide until a certain critical angle is reached.
- For the particular substances used in this demonstration (metal and wet glass), sliding begins at an angle of approximately 17°. Next, punch a small hole in the bottom of the can.

(2) Water

- Place it on the glass sheet and slowly pour some water into the open top (Fig. 6.16B). The can will begin to slide at a much gentler angle because the conditions at the base of the can have changed.
- In an analogous way, high water pressure at the base of a large mass of rock may promote downslope movement of the rock.
- These examples show that water can be instrumental in reducing shear strength and thereby promoting the movement of rock and sediment downslope under the pull of gravity.
- It does so by reducing the natural cohesiveness between grains or by reducing friction at the base of a mass of rock through increased water pressure.



F I G U R E 6.16 :An experiment illustrating how water can reduce friction at the base of a mass resting on a slope. A. An empty beverage can placed on a wet sheet of glass will begin to slide down the surface when the angle reaches about 17°. B. If a small hole is made in the bottom of the can and water is poured in through the top, the can will begin to slide down the slope at a much lower angle. In an analogous way, high water pressure at the base of a large rock mass may promote downslope movement of the rock.

(3) Troublesome Earth Materials

- Some Earth materials are particularly susceptible to the types of changes and disturbances that can lead to slope failure. Such materials, sometimes referred to as *problem soils,* are often involved in mass-wasting.
- **(3a) Liquefaction**
- As discussed earlier, when water is added gradually to a dry soil, the material first becomes **plastic**, or moldable. If enough water is added, the particles lose contact with one another and the material turns into a loose slurry, losing its shear strength in the process. **The transformation of a soil from a solid to a liquid state, usually (but not always) as a result of increased water content, is called liquefaction.**

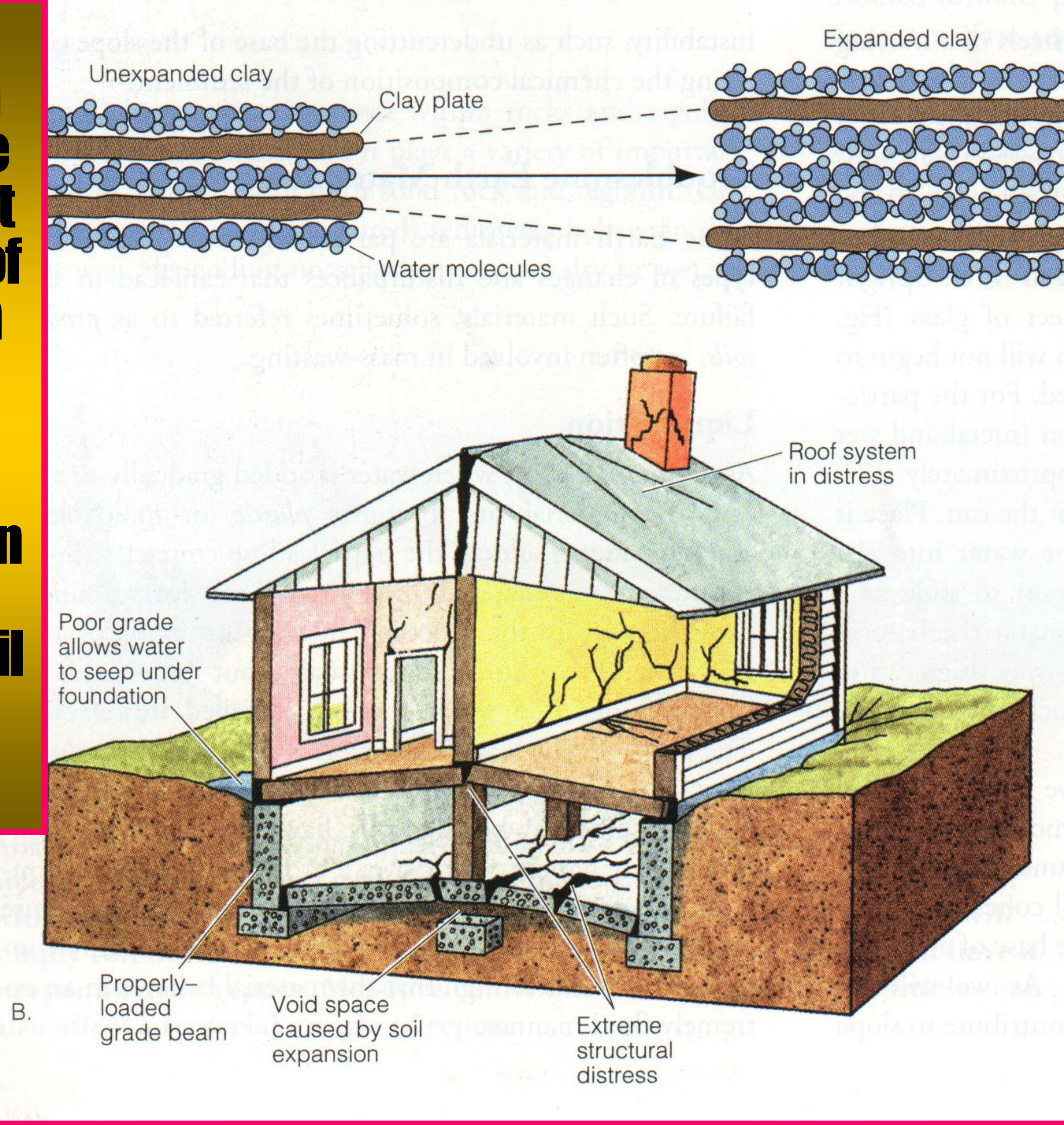
(3) Troublesome Earth Materials

- The point at which this transition occurs, called the **liquid limit**, varies from one soil to another.
- Some materials, particularly some clay-bearing soils, have very high liquid limits and may remain plastic over a broad range of water contents.
- These soils can be particularly troublesome because by the time the liquid limit is exceeded, the moisture content of the soil is so high that the material behaves in an extremely fluid manner.

(3b) Expansive and Hydrocompacting Soils

- **Expansive soils**, also referred to as **shrink—swell soils**, expand greatly when they are saturated with water and shrink when they dry out.
- Much of the increase in volume is caused by the chemical attraction of water molecules between the submicroscopic layers of clay minerals called *smectites* (Fig. 6.17A).
- Expansion resulting from increased water content can drastically reduce the shear strength of an Earth material, often contributing to downslope movement. It can also cause extensive damage to structures built on that material (Fig. 6.17B).

A. Expansion of a single smectite grain as a result of the addition of water between clay layers.
B. The type of structural damage that can result from the expansion of soil beneath a building.



(3b) Expansive and Hydrocompacting Soils

- When expansive clays dry out, they undergo a decrease in volume. The process of shrinkage and/or collapse resulting from water loss is referred to as **compaction** (or, more precisely, **hydrocompaction**, since soil compaction can be caused by other processes besides water loss).
- In addition to expansive clays, there are other types of soils that can exhibit substantial decreases in volume when they dry out.
- Extreme compaction associated with drying is a particular problem in water-saturated, organic-rich soils such as peat. Soil compaction often results in **subsidence**, **a type of mass movement involving the lowering or collapse of the ground surface.**

(3c) Sensitive Soils

- In some clay-rich soils, the particles are arranged in an open, porous structure like a house of cards (Fig. 6.18A). Such an arrangement can occur in very fine marine clays, in which salt acts to stabilize the "house of cards" by "gluing" the particles together end to end.
- Eventually, fresh groundwater may move through the area, changing the chemical composition of the clay and washing away the salt. Without the stabilizing effect of the salt, the clay particles collapse and take on a new, more compact arrangement.

Development of Quick-Clay Flows

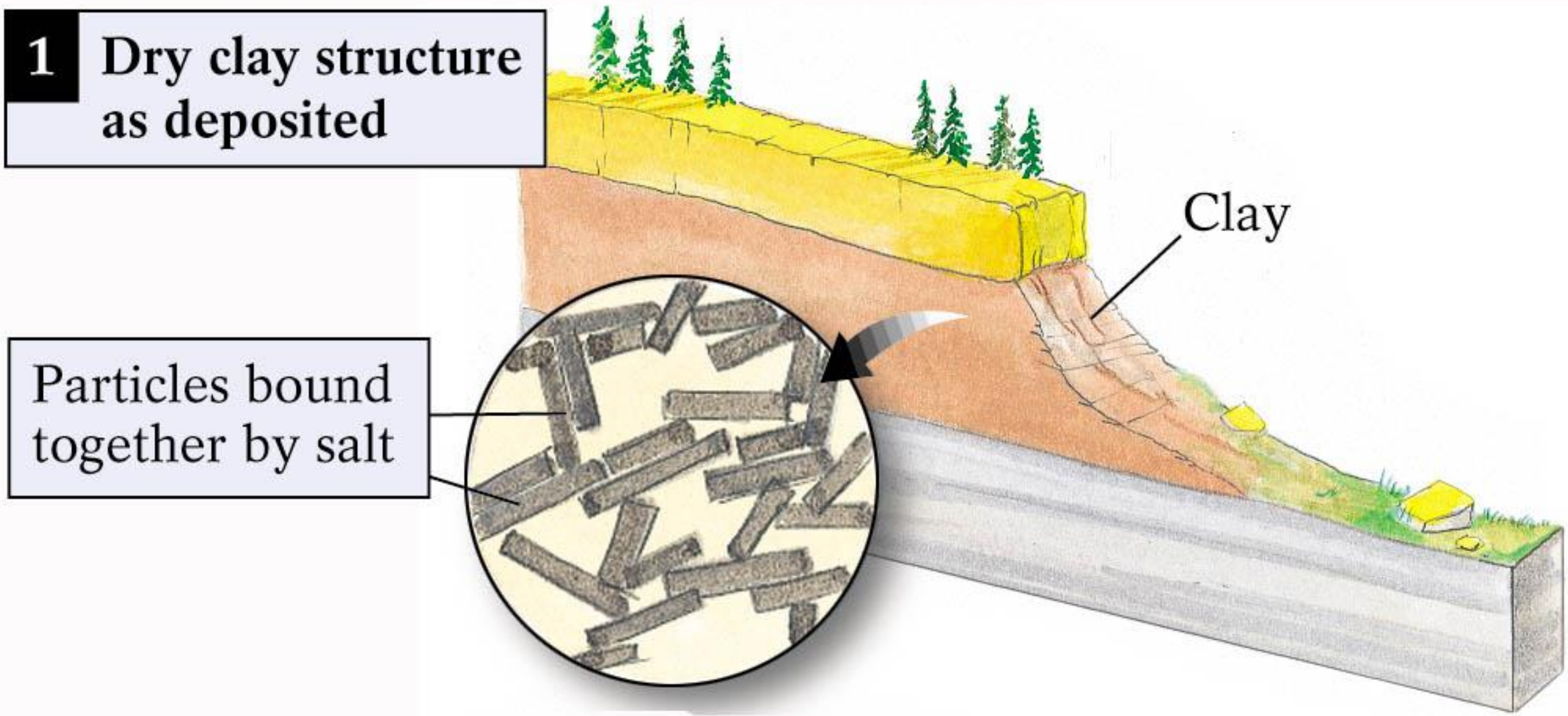
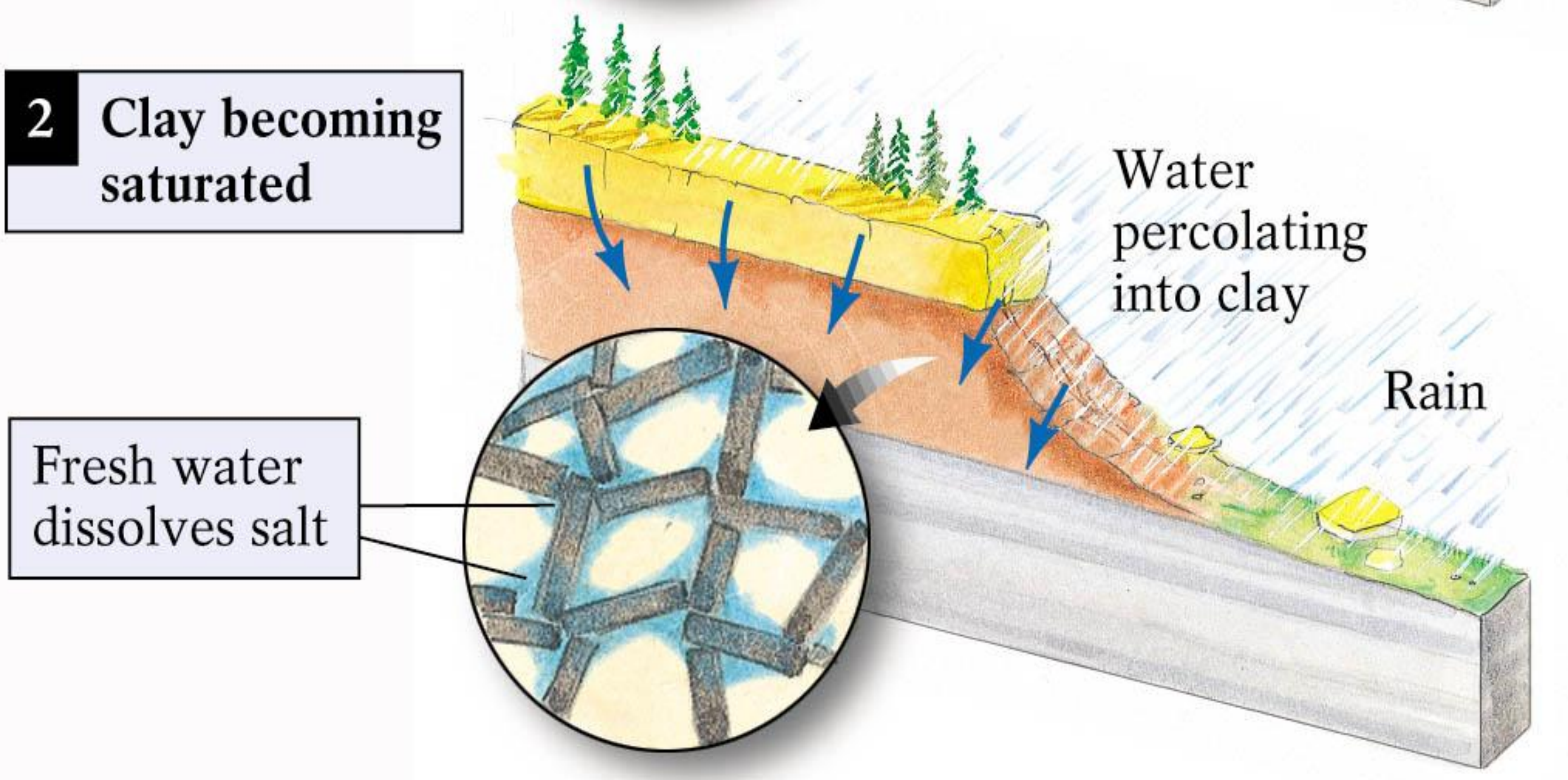
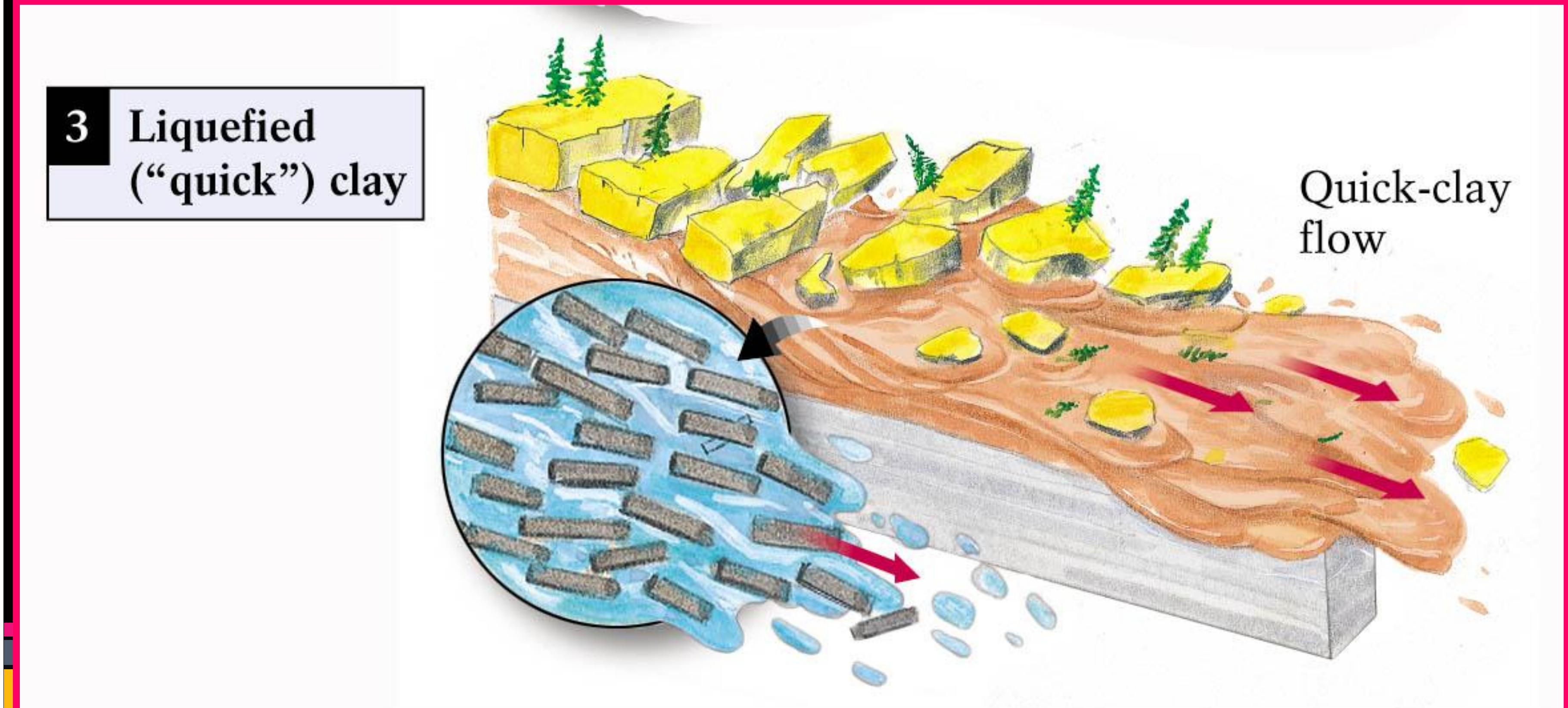


FIGURE 6.18 Sensitive clays. The "house-of-cards" structure of microscopic plates in a sensitive clay.

Development of Quick-Clay Flows

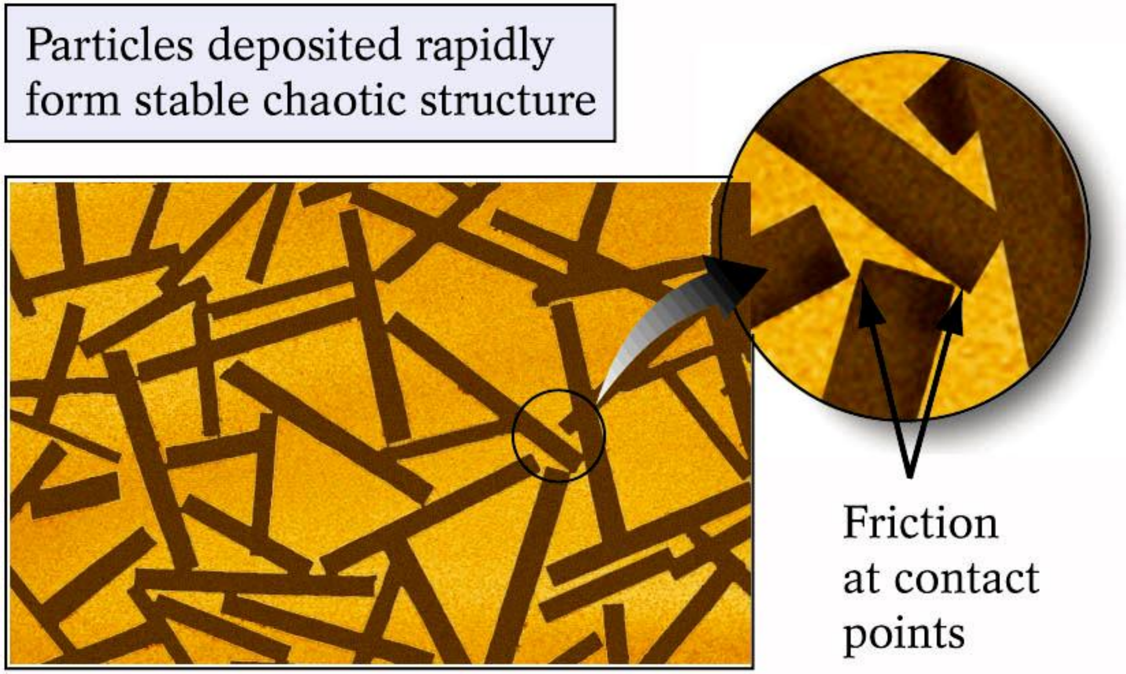


Development of Quick-Clay Flows

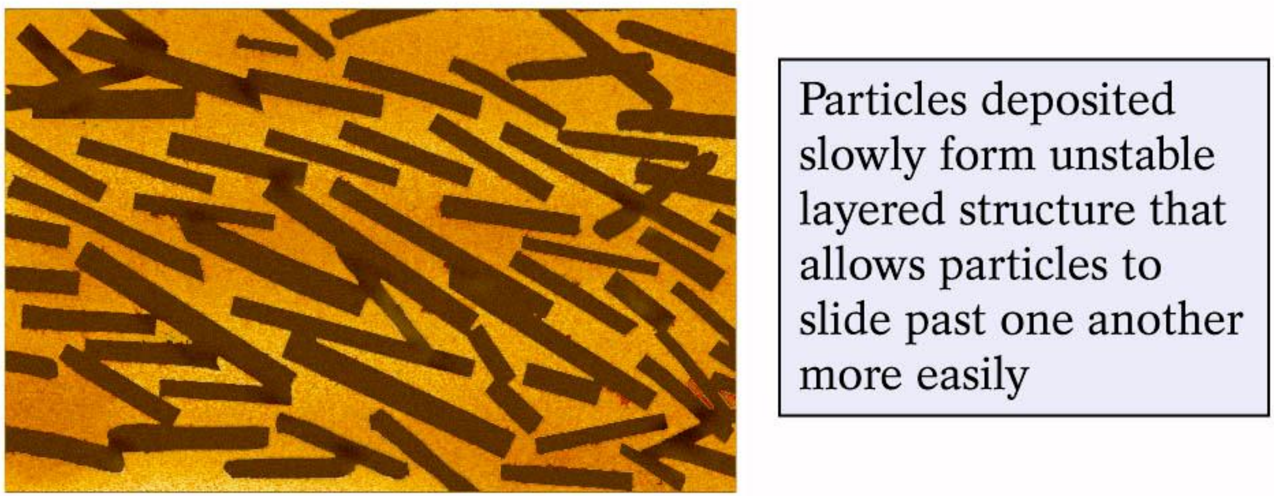


Structural change in a sensitive clay as a result of compaction, remolding, or thixotropism.

Effect of Particle Arrangement on Stability



(a) More stable structure



(b) Less stable structure

(3c) Sensitive Soils

- The transition from open to compact arrangement causes a sudden and dramatic loss of shear strength—in other words, **liquefaction**—which can propagate with astonishing speed throughout the entire mass of clay.
- Liquefaction or compaction that results from a disturbance of the internal structure of a soil is referred to as remolding.
- Materials that lose shear strength as a result of remolding are called **sensitive soils.**
- Those that are the most susceptible to remolding and liquefaction are called **quick clays.**
- Some other types of soils lose their shear strength suddenly when disturbed but gradually strengthen and resume their original properties when left undisturbed; these are referred to as **thixotropic clays.**

(4) Triggering Events

- Among the most common types of triggering events are earthquakes, volcanic eruptions, slope modifications, and changes in the hydrologic characteristics of an area (including the effects of prolonged or exceptionally intense rainfall).
- **(4a) Earthquakes and Other Shocks**
- An abrupt shock, such as an explosion, an earthquake, an electrical storm, or even a truck passing by, can increase shear stress and contribute to slope failure. Intense shaking can cause a buildup of water pressure in the pore spaces of a sediment, leading to liquefaction.

(4a) Earthquakes and Other Shocks

- In other words, liquefaction is not always related to an increase in water content; sometimes shaking causes the pore water **already** present in the sediment to coalesce so that the sediment grains lose contact with one another.
- The result is fluidization of the sediment and abrupt failure. Any structure built on such sediments or in their path may be demolished (Fig. 6.19).
- Major submarine turbidity currents and slumps off eastern North America are also known to have been caused by strong earthquakes.

FIGURE 6.19:Chaotically tilted trees and houses in suburbanAnchorage, show how violent shaking of the ground during earthquake caused sudden liquefaction of underlying clays and widespread slumping.

(4b) Volcanic Eruptions

- Volcanic eruptions are another mechanism for triggering mass-wasting events. Large stratovolcanoes consist of inherently unstable accumulations of interlayered lava flows, rubble, and pyroclastic material that form steep slopes.
- The slopes of high, ice-clad volcanoes may be further steepened by glacial erosion. Large volumes of water, released when summit glaciers and snowfields melt during an eruption of hot lavas or pyroclastic debris, can combine with unconsolidated deposits to form rapidly moving lahars.
- As in the case of Armero, Colombia, these highly fluid mudflows can travel great distances and at such high velocities that they constitute one of the major hazards associated with volcanic eruptions.

(4c) Slope Modifications and Undercutting

- Landslides often result when natural slopes are modified, either by natural processes or by human activities. **Translational slides** can occur, for example, where roads have been cut into regolith or unstable rock, creating an artificial slope that exceeds the angle of repose or exposes natural planes of weakness (Fig. 6.22).
- Such landslides are especially common along mountainous and coastal cliffs where roads have been carved into deformed sedimentary or metamorphic rocks.

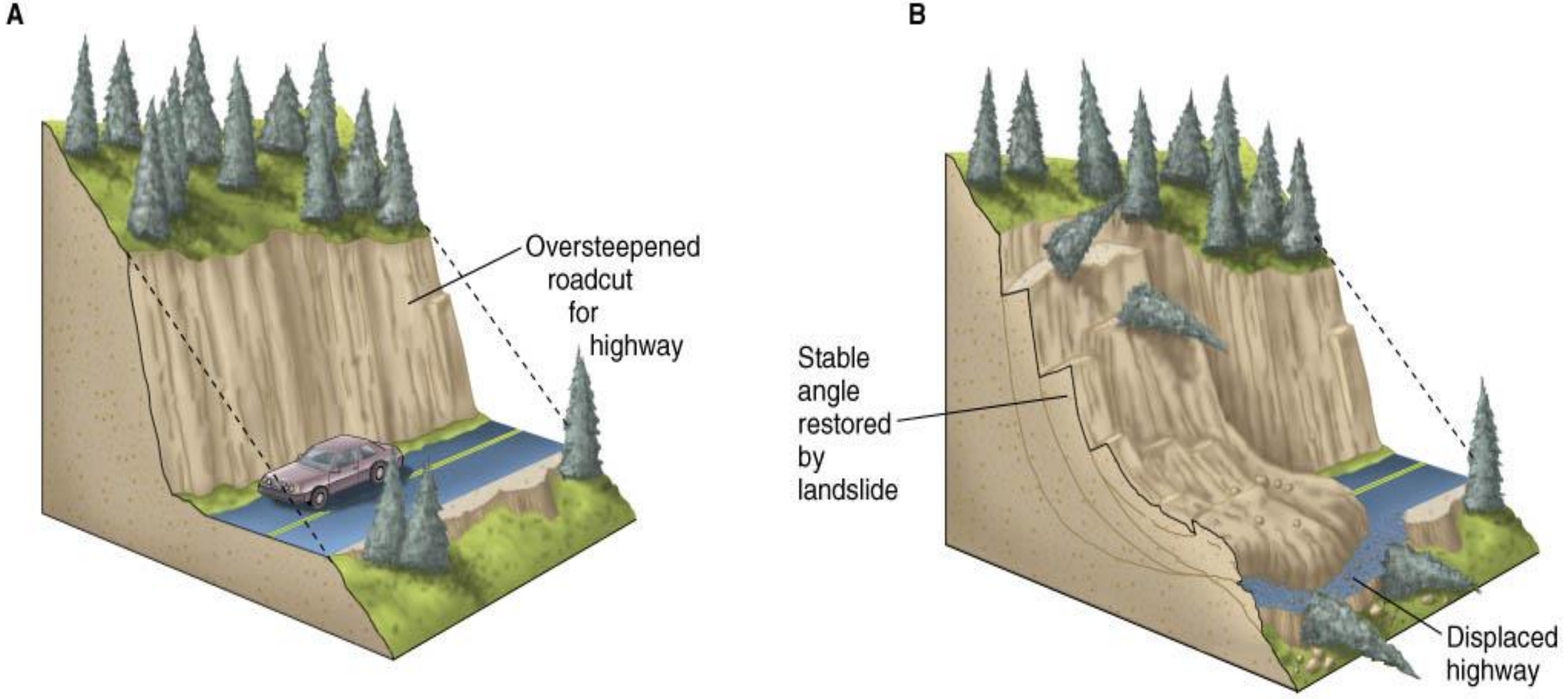


FIGURE 6.22: Modification of a slope during road construction can lead to slope failure. A. The natural angle of repose of the material in the slope is exceeded. B. The oversteepened slope fails, and a landslide buries the road.

(4c) Slope Modifications and Undercutting

- Overloading—placing a building or a mass of excavated material at the top of a slope, for example—can also contribute to slope failure because of the added weight as well as the steepening effect of the load.
- In 1966, for example, excessive rain in Rio de Janeiro caused an **oversteepened** slope in a road cut to fail. The mass of material involved in this small slide overloaded the top of the underlying slope, triggering a large landslide that destroyed several houses and two apartment buildings and killed 132 people

(4c) Slope Modifications and Undercutting

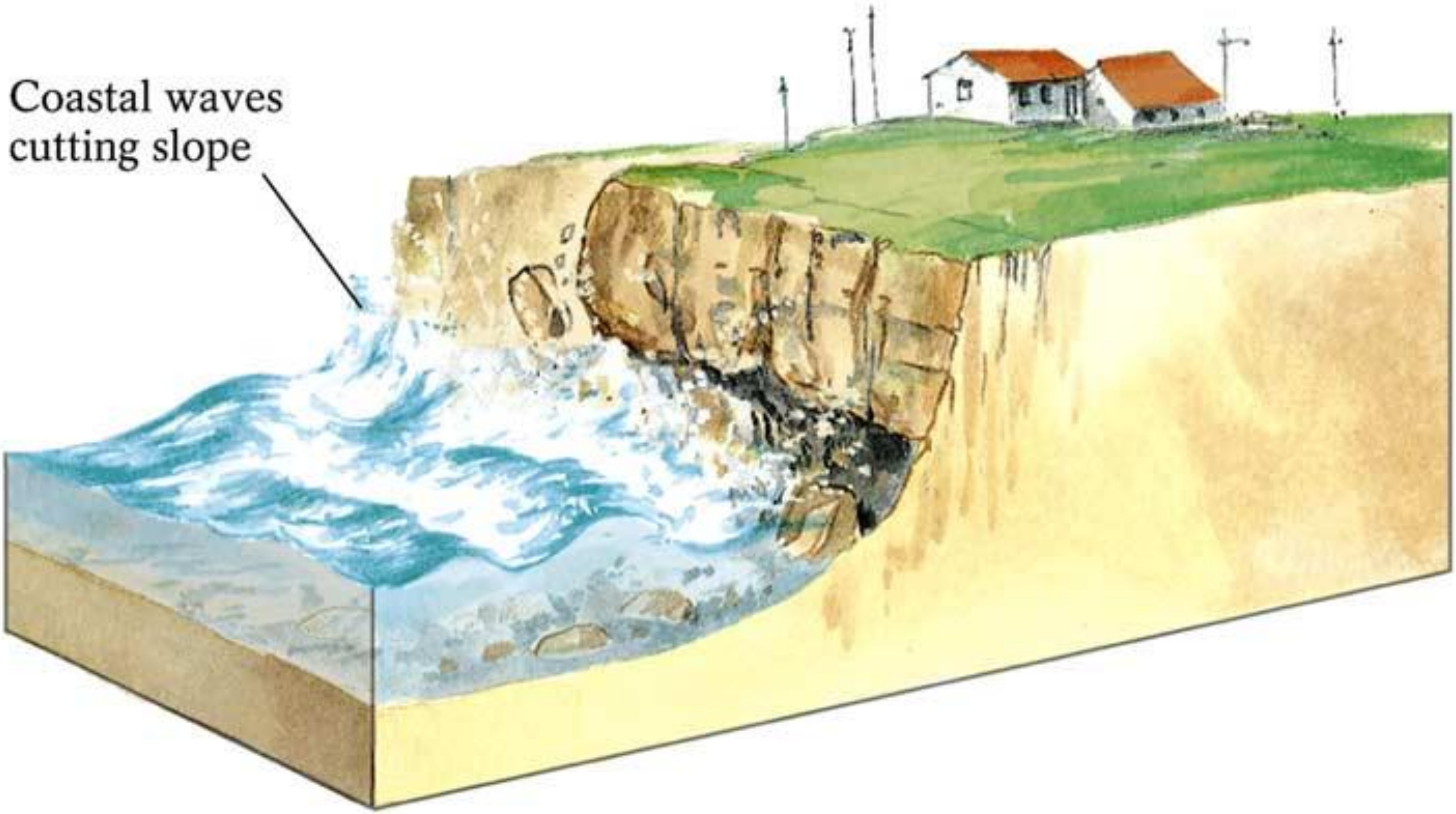
- Perhaps the most famous example occurred in 1966 in the coal-mining town of **Aberfan in Wales**. The debris left over from the mining process—mostly very fine clay, in this case—was routinely piled up in large artificial hills called **tips**.
- One morning in October, a major slope failure occurred on one of the tips. It was later determined that drainage within the tip had been inadequate, resulting in saturation and eventually liquefaction of the lower portion.
- The upper part of the tip moved as a coherent mass, carried along on the liquefied material below. When the mass of fluidized material came to rest, it had lost most of its water content and returned to its original solid state.

(4c) Slope Modifications and Undercutting

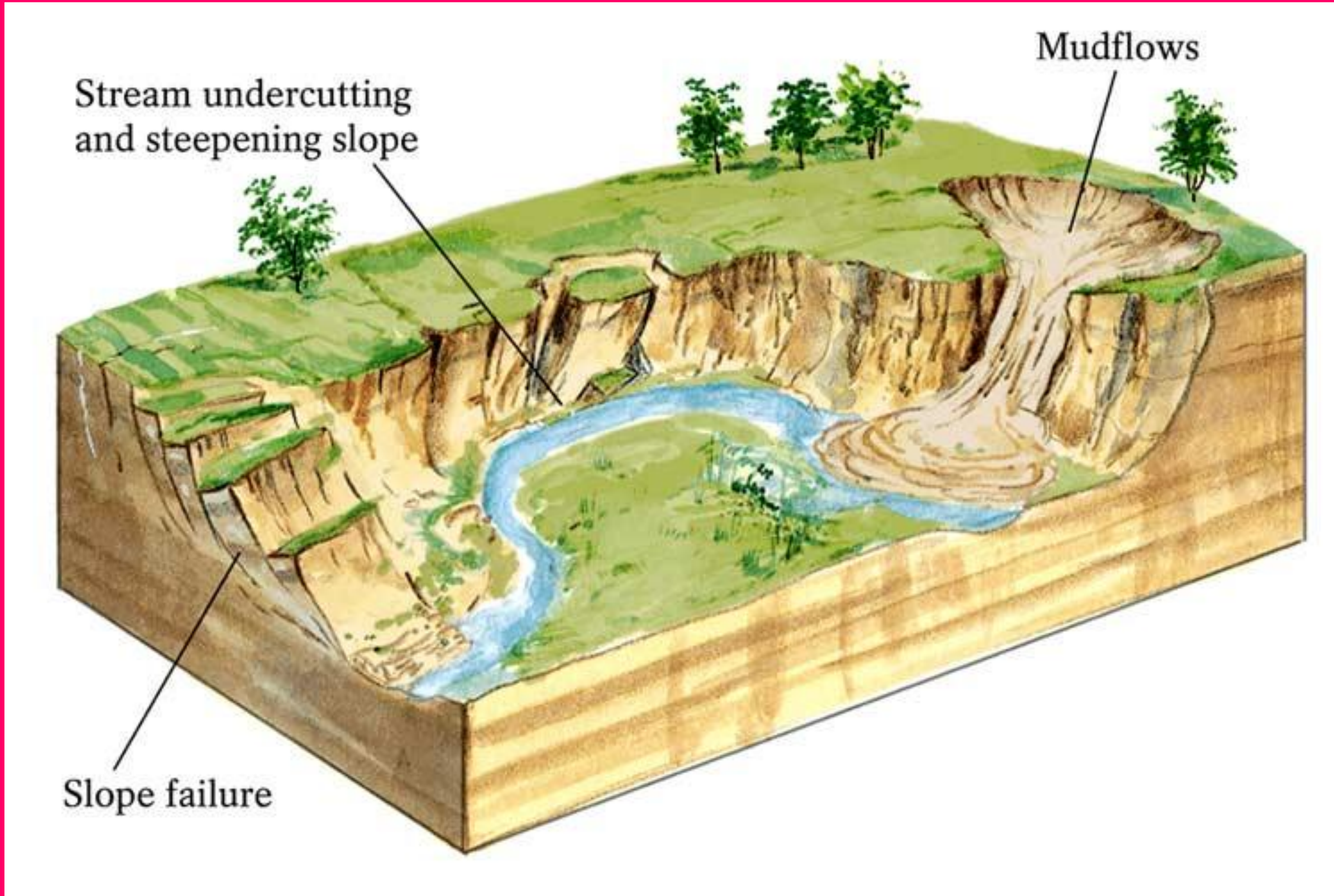
- Slumps and other types of landslides can also be triggered by the <u>natural steepening of slopes as a result of the undercutting action of a stream along its bank or waves along a coast.</u>
- Coastal landslides are often associated with major storms that direct their energy against rocky headlands or the bases of cliffs composed of unconsolidated sediments (Fig. 6.25).

A FIGURE 6.25: Steep cliffs along the coast of Hawaii are undercut by pounding surf. When a cliff collapses, the resulting landslide debris is rapidly reworked by

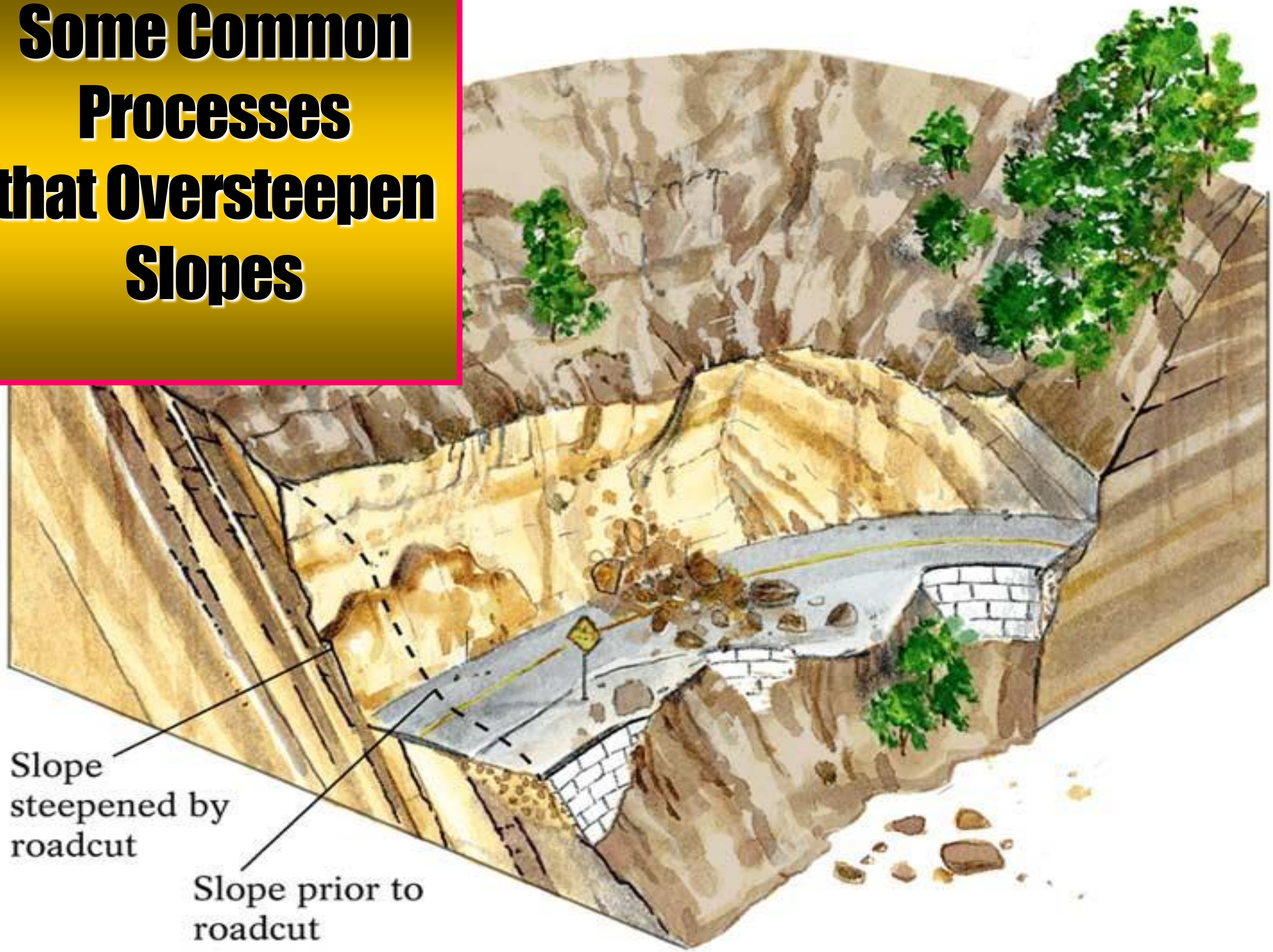
Some Common Processes that Oversteepen Slopes



Some Common Processes that Oversteepen Slopes



Some Common Processes that Oversteepen Slopes



(4d) Changes in Hydrologic Characteristics

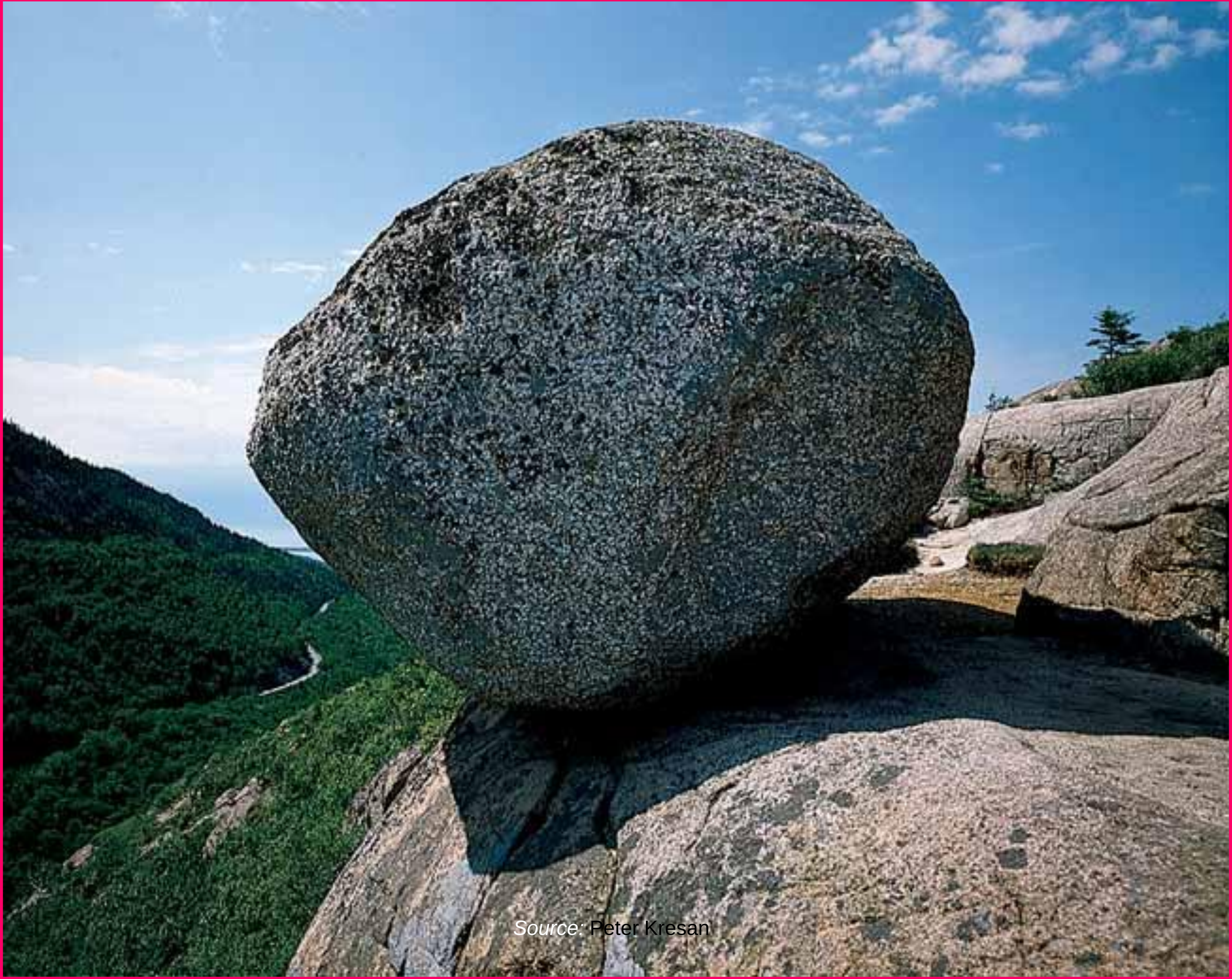
- Changes in the characteristics of subsurface water or drainage in an area often contribute to landslides. For example, heavy or persistent rains may saturate the ground and make it unstable. Such was the case in 1925 when prolonged rains, coupled with melting snow, started a large debris flow in the Gros Ventre River basin of western Wyoming.
- The water saturated a porous sandstone overlying an impermeable rock unit that sloped toward the valley floor. This water-saturated condition was an ideal trigger for slope failure. An estimated 37 million m^3 of rock, regolith, and organic debris moved rapidly downslope and created a natural dam that ponded the river.

(4d) Changes in Hydrologic Characteristics

- The filling of a large reservoir can also cause changes in subsurface water conditions. Sometimes the increased water pressure in the pores of the underlying rock combines with other destabilizing factors to produce mass-wasting. Such factors caused the world's worst dam disaster, which occurred in Italy in 1963. A huge mass—almost 250,000,000 m^3—of rock and debris slid into the reservoir behind the Vaiont Dam.
- The material filled the reservoir and created a wave 100 m high, which overflowed the dam and swept both up and down the valley, killing almost 3000 people. There were several driving forces in this event: the slopes were composed of inherently unstable blocks of limestone, with open fractures dipping toward the reservoir; the water impounded in the reservoir had increased pore water pressure in the rock walls of the valley.

ASSESSING AND MITIGATING MASS-WASTING HAZARDS

- Landslides and other forms of mass-wasting are ubiquitous, and they cause extensive damage and loss of life each year. With careful analysis and planning, together with appropriate stabilization techniques, the impacts of mass-wasting processes on humans can often be reduced or eliminated.
- Maps showing areas that could be affected by mass-wasting events are important tools for land-use planners. For example, large debris avalanches and small rockfalls are ever-present hazards in the northern Italian Alps (Fig. 6.29). Field studies have shown that large debris avalanches have repeatedly blanketed valley floors with rocky debris during the last 3000 years.

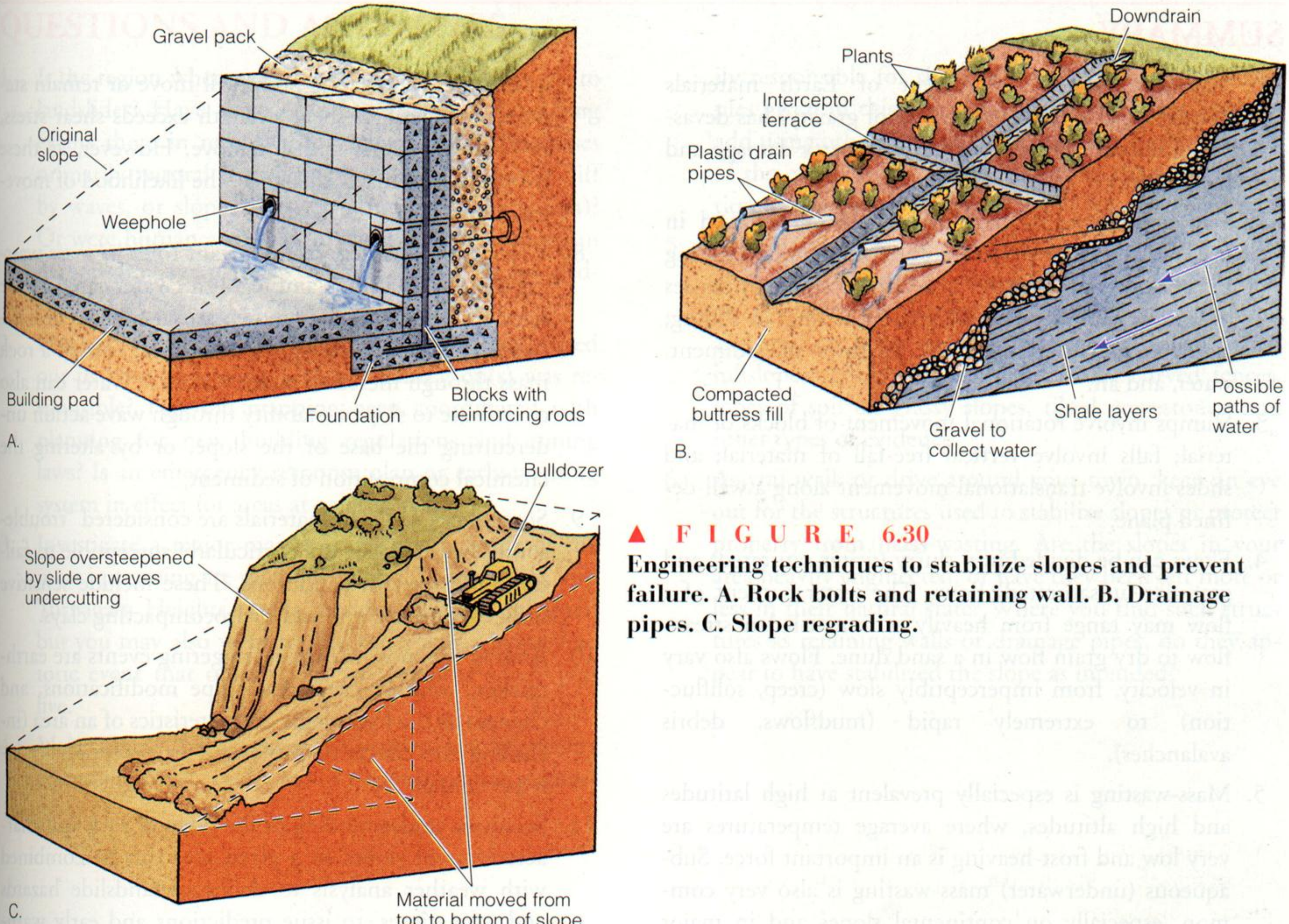

Source: Peter Kresan


17/02/2007

FIGURE 6.29:A new apartment building at the base of a steep mountain slope in the Italian Alps was struck by a large boulder falling from the cliffs above. This relatively small rockfall, which occurred just one day before the new owners were to move in,

Assessing And Mitigating Mass-Wasting Hazards

- From this evidence, a map has been constructed showing areas that could be affected by future rockfalls with various trajectories and distribution patterns.
- Eliminating or restricting human activities in areas where slides are likely to occur may be the best way to mitigate such hazards. For example, land that is susceptible to mild failures might be suitable for some types of development (e.g., recreation or parkland) but not others (e.g., intensive agriculture or housing).
- In addition to assessment, prediction, and early warning, some engineering techniques can be used to mitigate or even prevent landslides. These include retaining devices; drainage pipes; grading; and diversion walls (Fig. 6.30).



▲ FIGURE 6.30

Engineering techniques to stabilize slopes and prevent failure. A. Rock bolts and retaining wall. B. Drainage pipes. C. Slope regrading.

Assessing And Mitigating Mass-Wasting Hazards

- One of the most common approaches is the use of concrete block walls, poured or sprayed concrete, rock bolts, or gabions (rocks contained in wire mesh cages) to strengthen slopes (Fig. 6.30A).
- Slopes that are subject to creep can be stabilized by draining or pumping water from saturated sediment (Fig. 6.30B); this is accomplished by the insertion of permanent drainage pipes, often in combination with a wall.
- Over steepened hill slopes can be prevented from slumping if they are regarded to angles equal to or less than the natural angle of repose.

Assessing And Mitigating Mass-Wasting Hazards

- **There are some other steps that can be taken to reduce actual landslide hazards.**
- **(1) Slope Reduction**
- If a slope is too steep to be stable under the load it carries, any of the following steps will reduce slide potential: (1) reduce the slope angle, (2) place additional supporting material at the foot of the slope to prevent a slide or flow at the base of the slope, or (3) reduce the load (weight, shearing stress) on the slope by removing some of the rock or soil (or artificial structures) high on the slope.

Engineering Stable Slopes

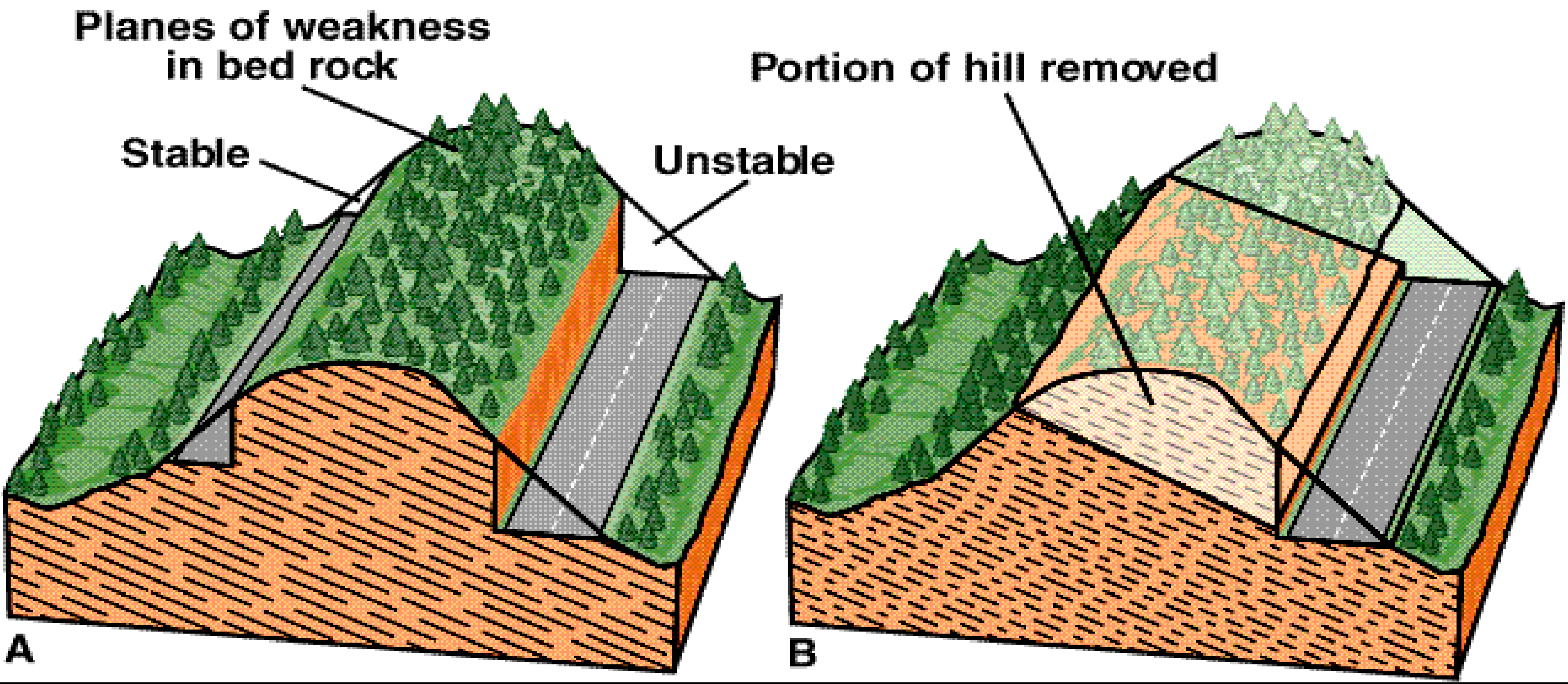
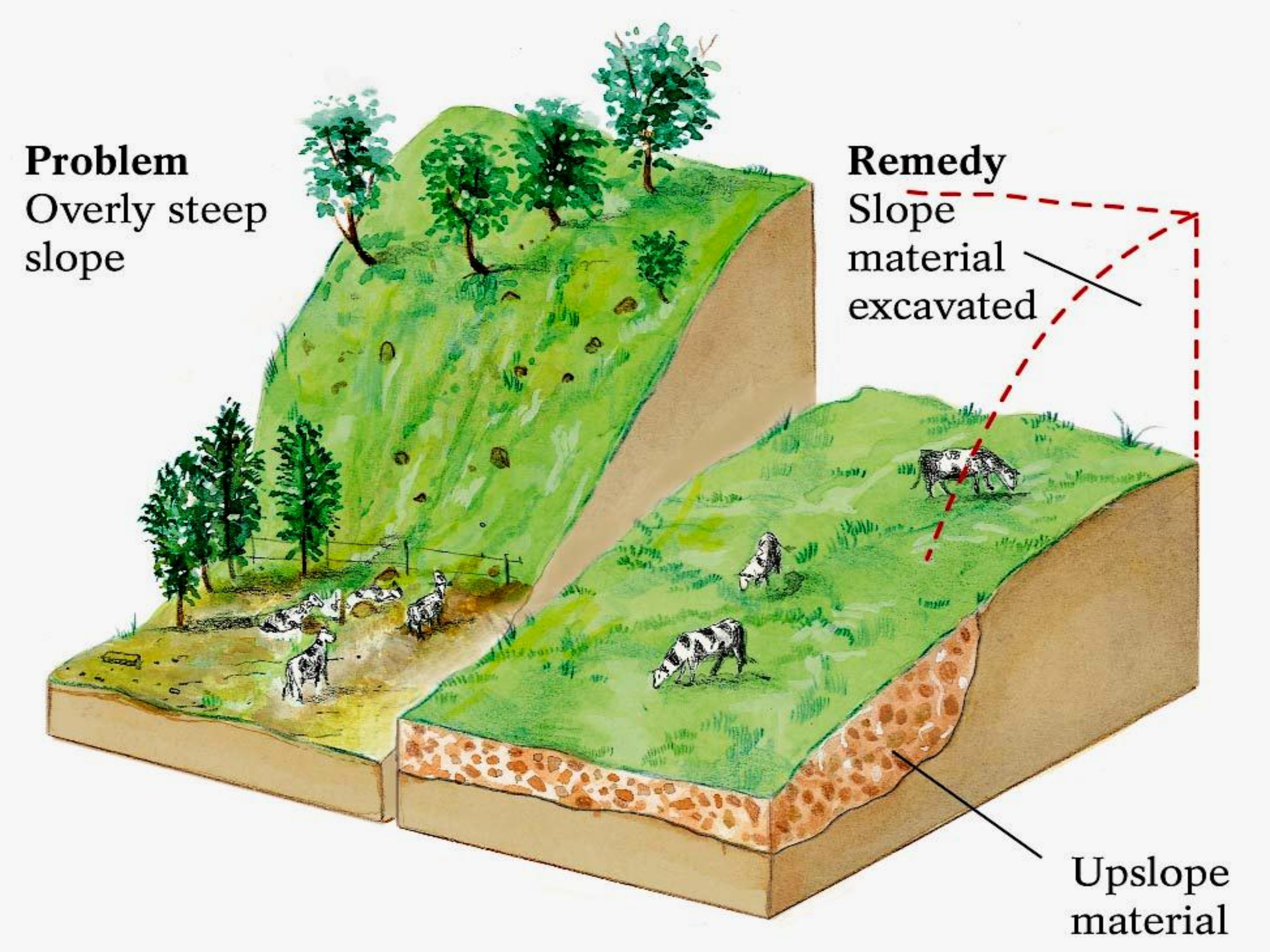


Figure 8.22: Slope stabilization by slope reduction and removal of unstable material along roadcut. (4) Before: Roadcut leaves steep, unsupported slope. (B) After: Material removed to reduce slope angle and load.


Problem
Overly steep slope
Remedy
Slope material excavated
Upslope material

Assessing And Mitigating Mass-Wasting Hazards

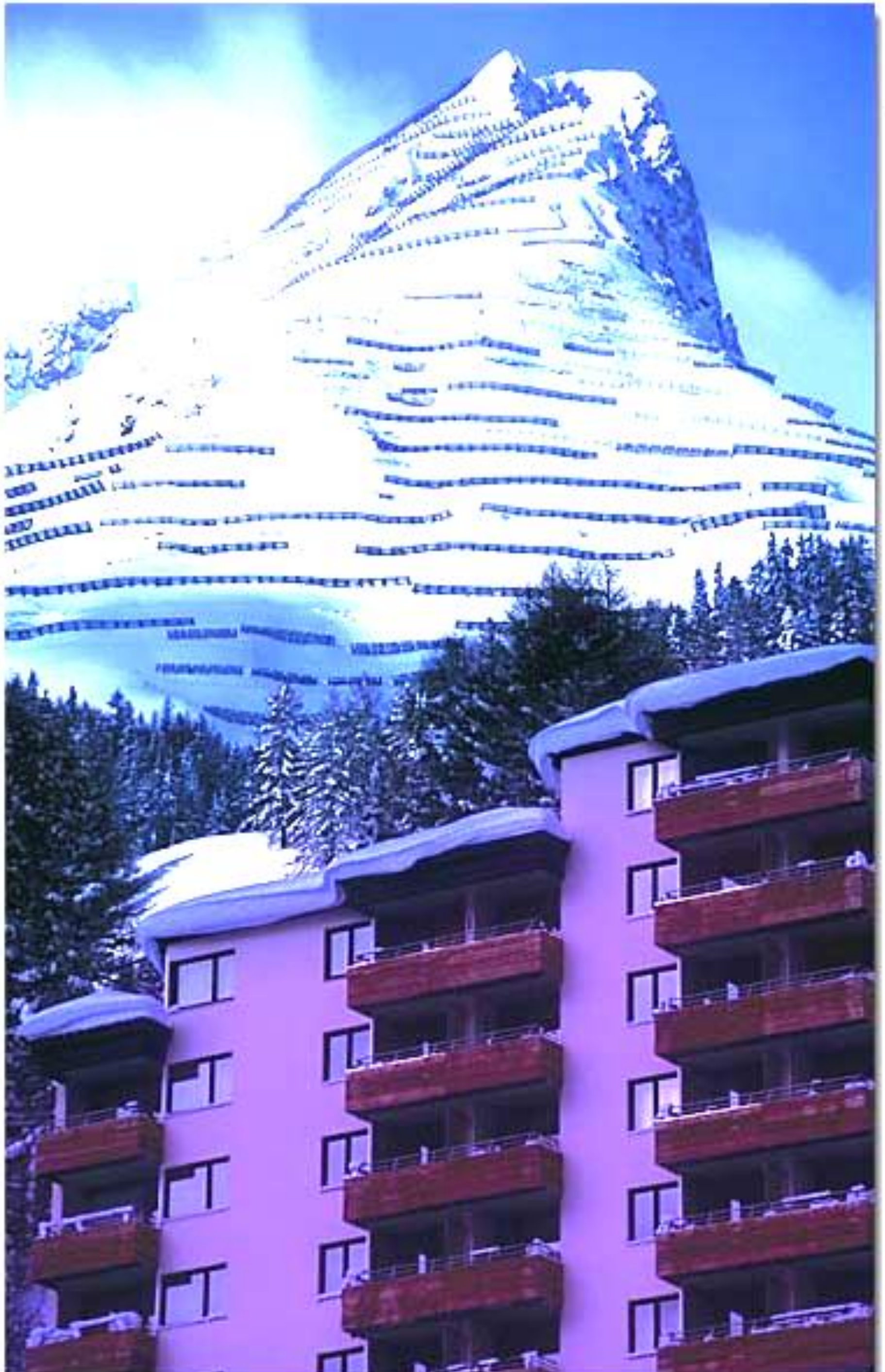
- **(2) Retention Structures**
- To stabilize exposed near-surface soil, ground covers or other vegetation may be planted (preferably fast-growing materials with sturdy root systems). But sometimes plants are insufficient, and the other preventive measures already described impractical, in a particular situation. Then, retaining walls or other stabilization structures can be built against the slope to try to hold it in place (figures 8.23, 8.24).
- Given the distribution of stresses acting on retaining walls, the greatest successes of this kind have generally been low, thick walls placed at the toe of a fairly coherent slide to stop its movement.

In many areas rock faces are ‘stitched’ with massive steel bolts to try to keep material from being lost to active weathering.

Alternately, surfaces can be covered with strong mesh or boulder catching nets can be used.

Closeup shows that somewhat naturalistic appearance is achieved by building structure of rock rubble encased in chain-link fencing.


Soil
Nailing



"Davos-II"
© François Portmann.
New York City, New York, U.S.A.

Best Photo on
Mountain Environment
[illegible] Banff Mountain
Photography Competition

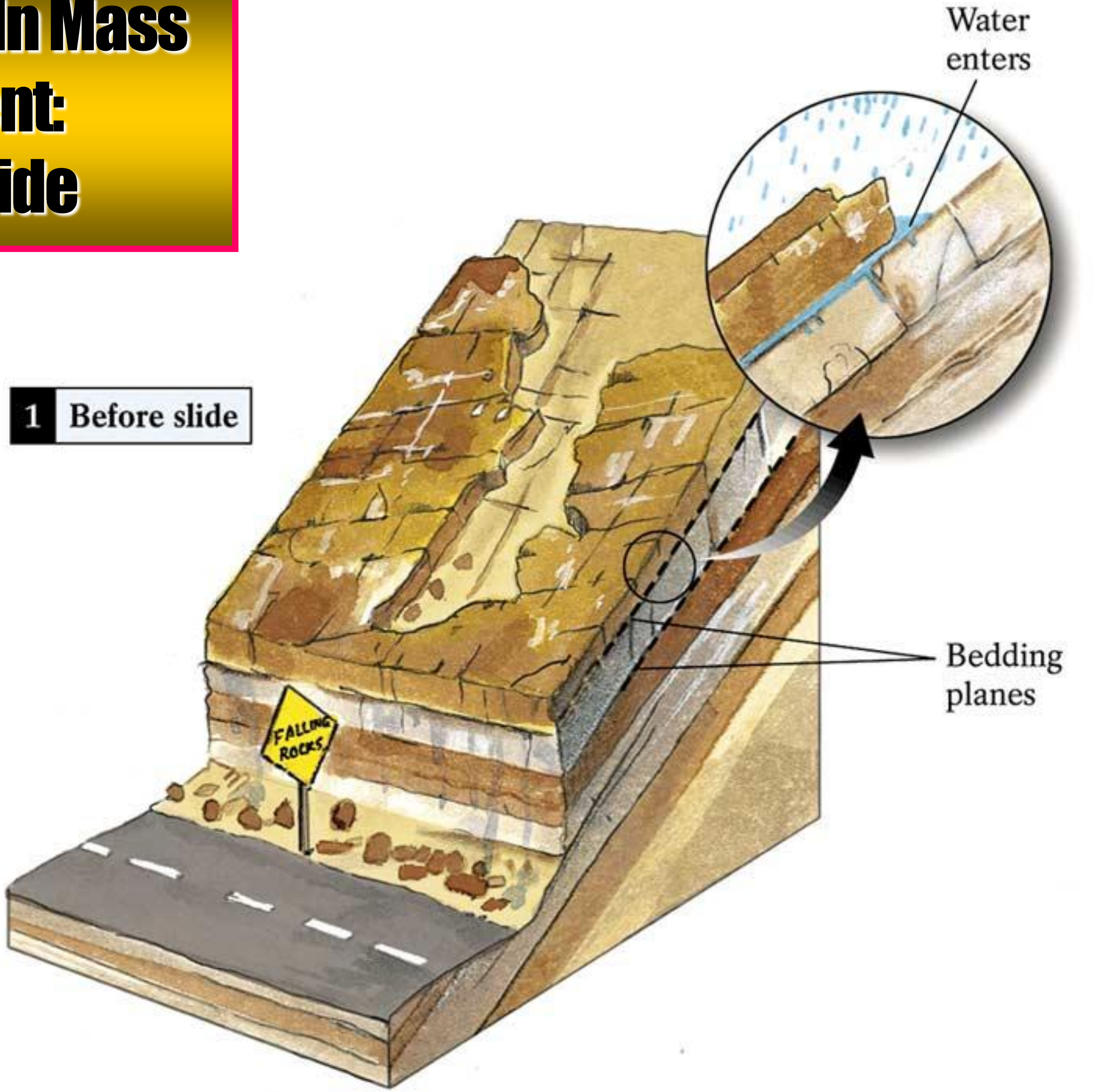
Avalanche Barriers Switzerland

Assessing And Mitigating Mass-Wasting Hazards

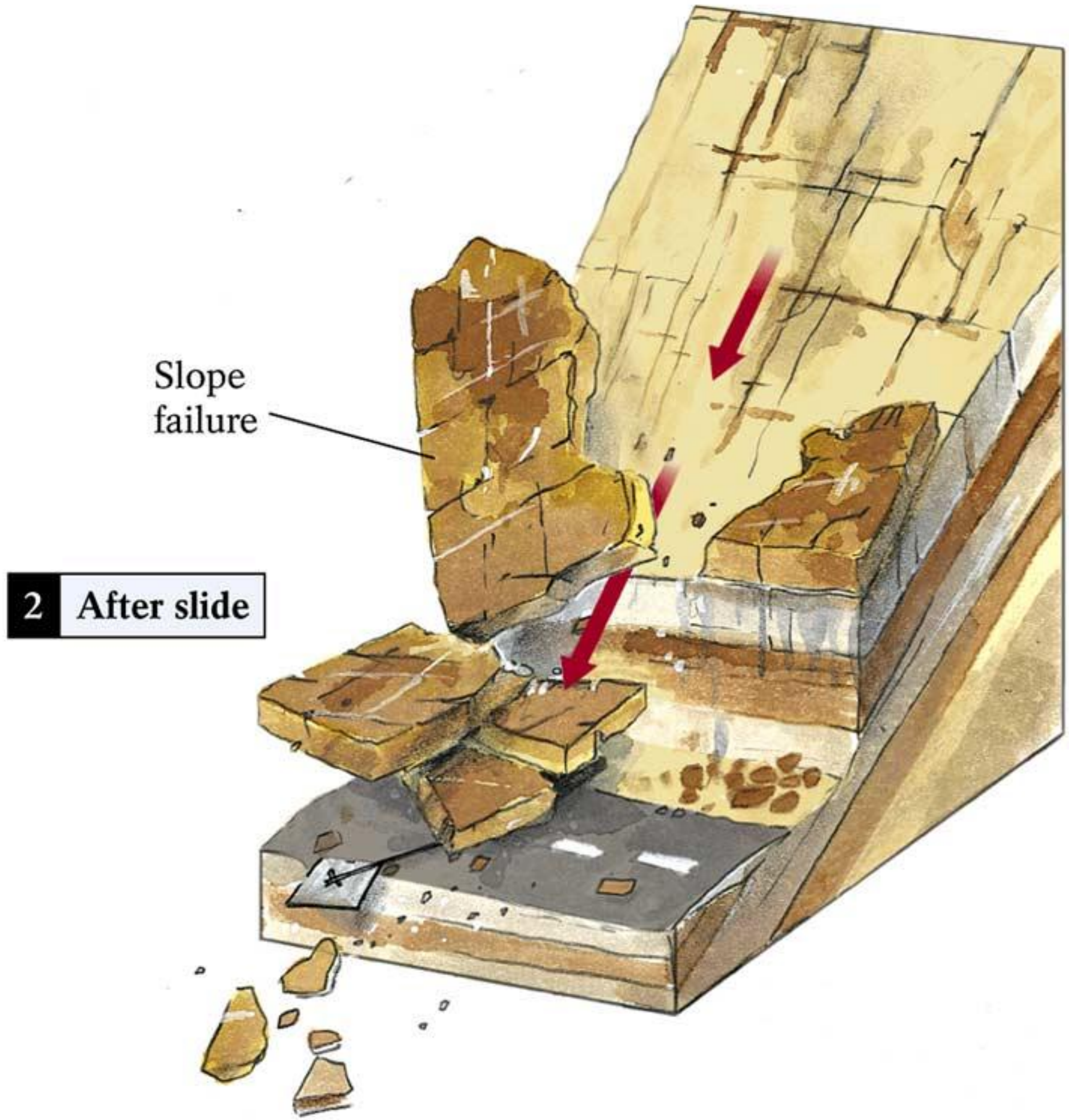
- ## (3) Fluid Removal
- Since water can play such a major role in mass movements, the other principal strategy for reducing landslide hazards is to decrease the water content or pore pressure of the rock or soil. This might be done by covering the surface completely with an impermeable material and diverting surface runoff above the slope.

- Alternatively, subsurface drainage might be undertaken. Systems of underground boreholes can be drilled to increase drainage and pipelines installed to carry the water out of the slide area (figure 8.25). All such moisture-reducing techniques naturally have the greatest impact where rocks or soils are relatively permeable. Where the rock or soil is fine-grained and drains only slowly, hot air may be blown through boreholes to help dry out the ground. Such moisture reduction reduces pore pressure and increases frictional resistance to sliding.

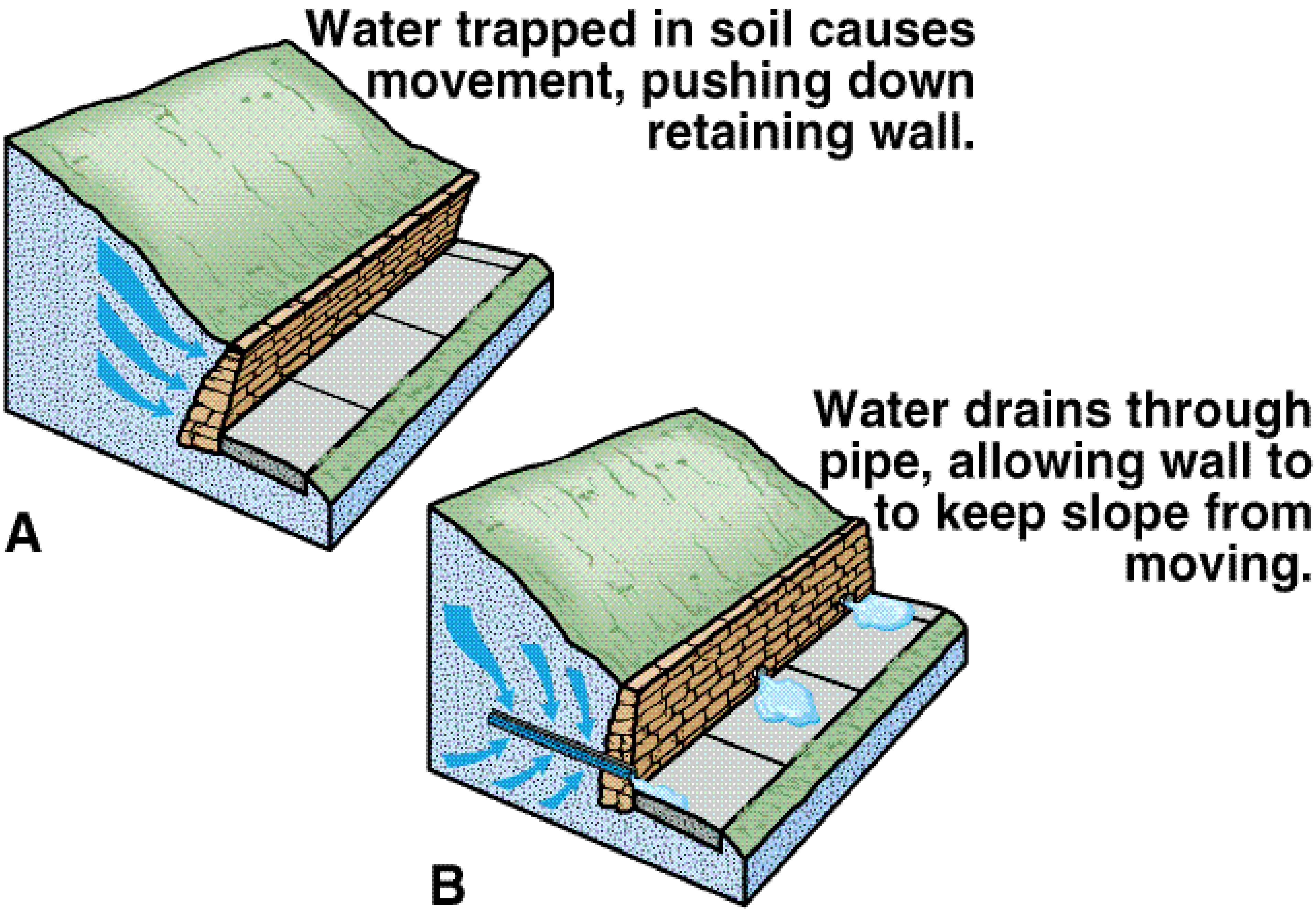
Water's Role In Mass Movement: Before Slide



Water's Role In Mass Movement: After Slide

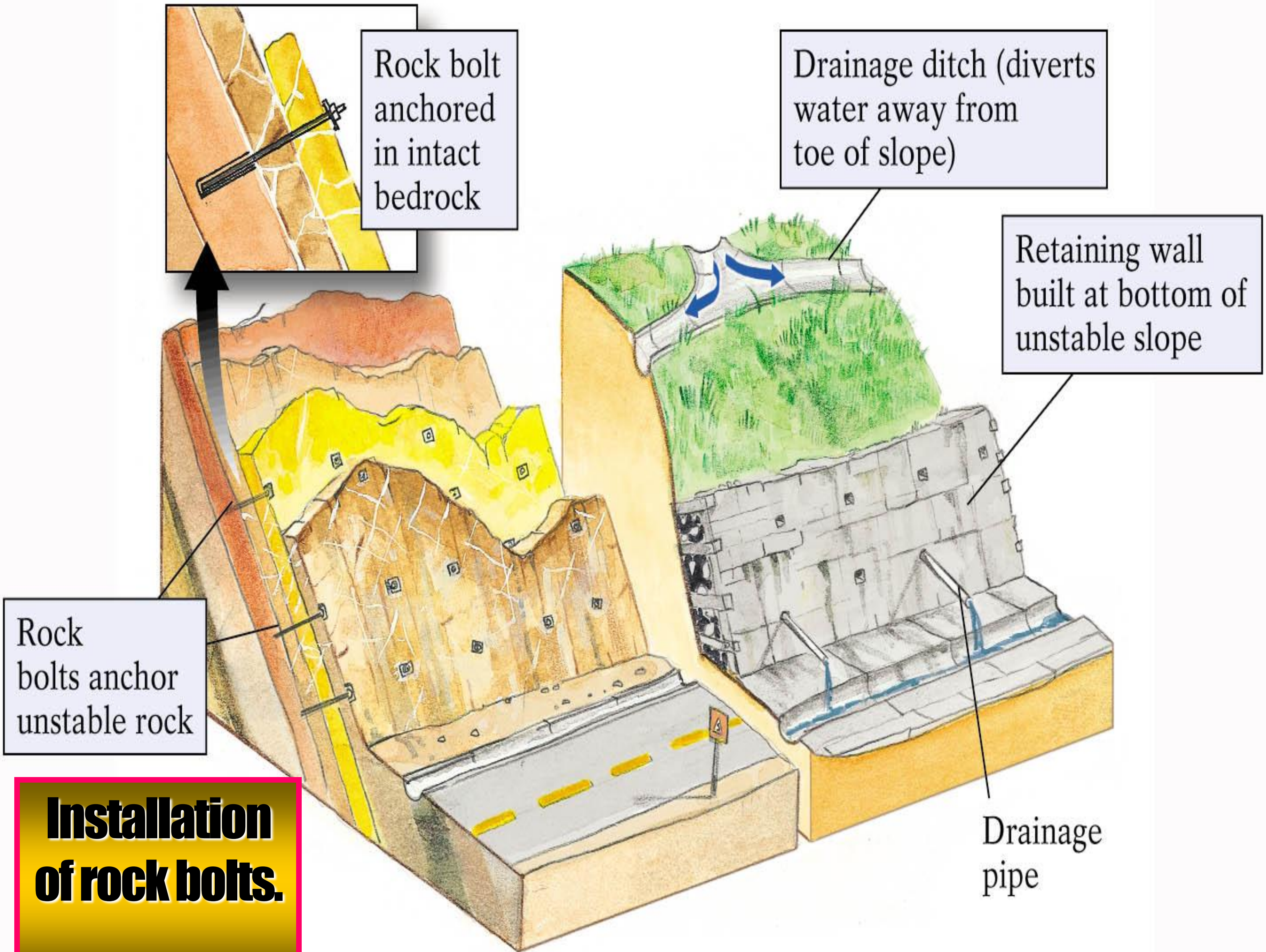


Mass Wasting Prevention

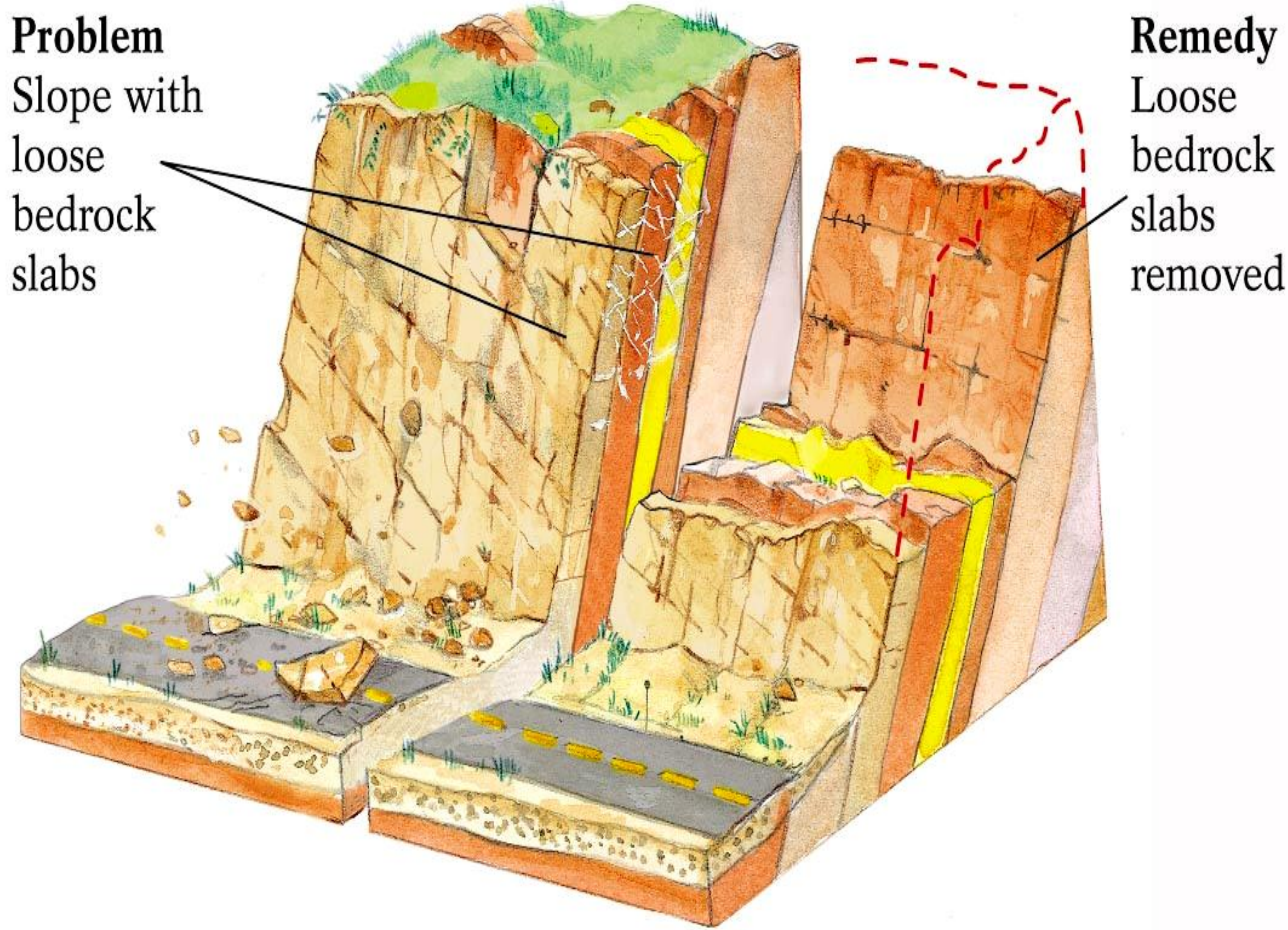


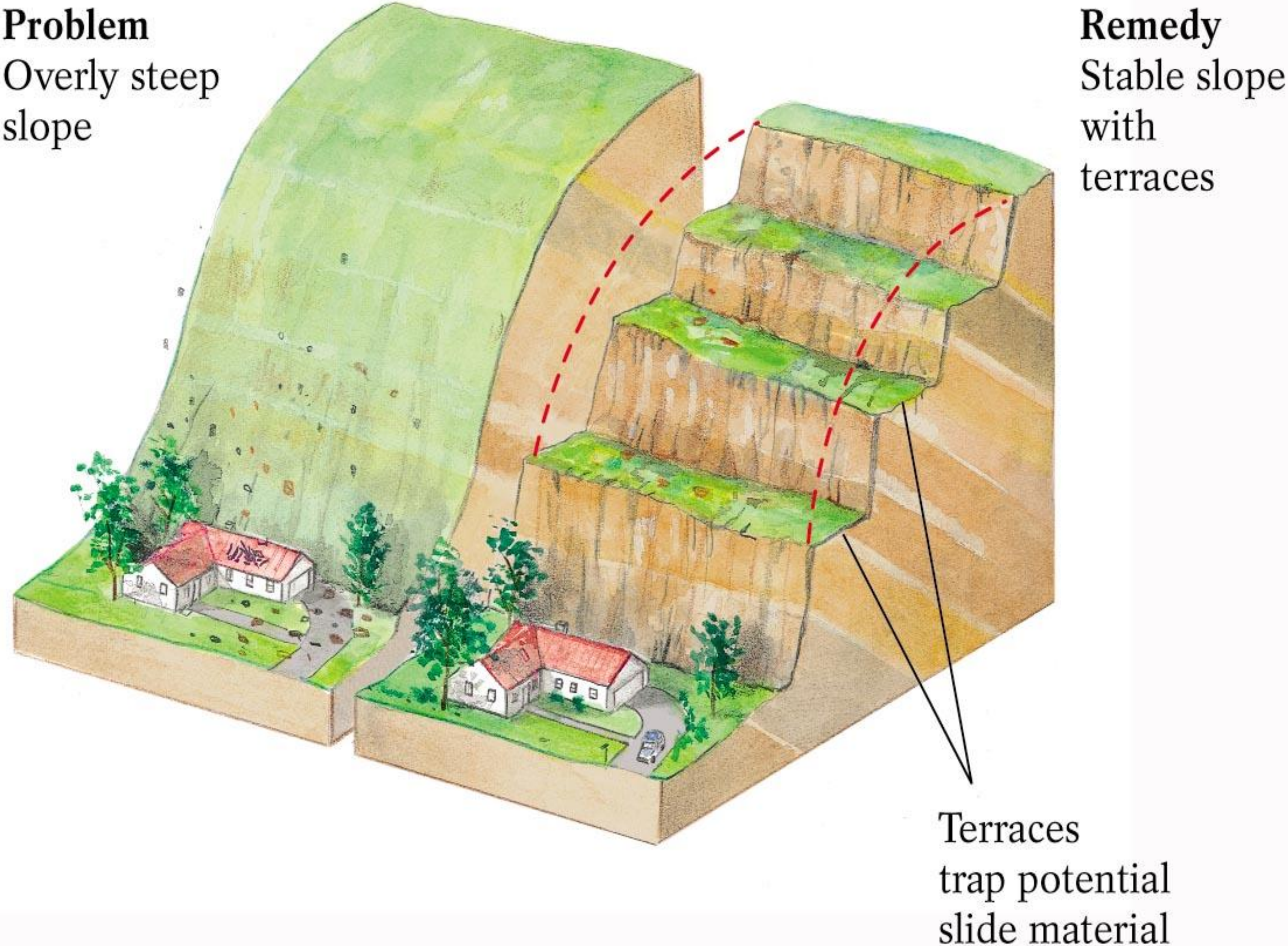
Assessing And Mitigating Mass-Wasting Hazards

- **Other Slope-Stabilization Measures**
- The use of rock bolts to stabilize rocky slopes and, occasionally, rockslides has had greater success (figure 8.26). Rock bolts have long been used in tunneling and mining to stabilize rock walls. It is sometimes also possible to anchor a rockslide with giant steel bolts driven into stable rocks below the slip plane. Again, this works best on thin slide blocks of very coherent rocks on low-angle slopes.
- Procedures occasionally used on unconsolidated materials include hardening unstable soil by drying and baking it with heat (this procedure works well with clay-rich soils) or by treating with portland cement. By far the most common strategies, however, are modification of slope geometry and load, dewatering, or a combination of these techniques.



Installation of rock bolts.


Problem
Slope with loose bedrock slabs
Remedy
Loose bedrock slabs removed

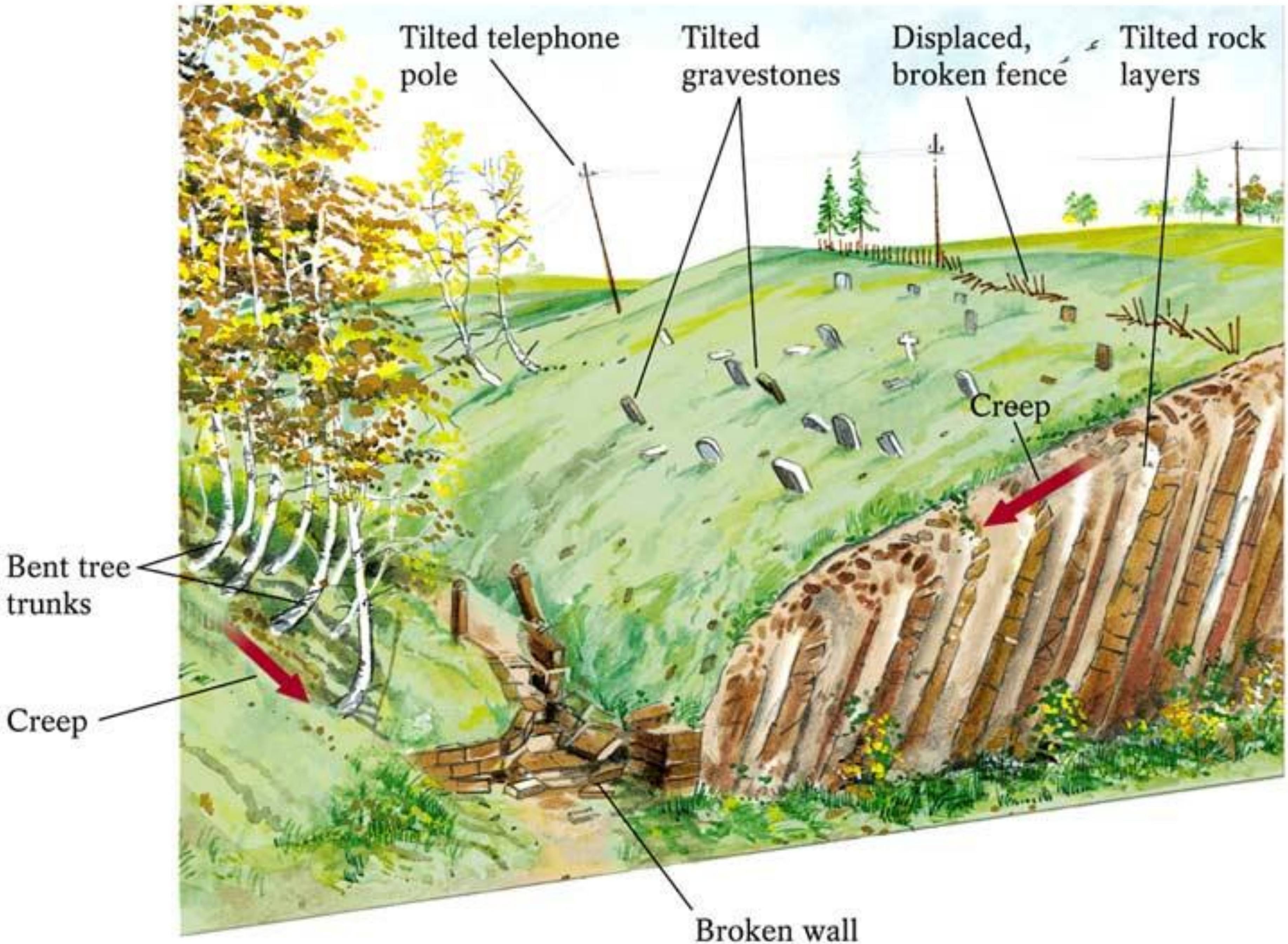

Problem
Overly steep
slope
Remedy
Stable slope
with
terraces
Terraces
trap potential
slide material

Recognizing the Hazards

- Recognizing past rockfalls can be quite simple, especially in vegetated areas. Large chunks of rock are inhospitable to most vegetation, so rockfalls tend to remain barren of trees and plants. The few trees that do take hold may only contribute to further breakup by root action. Lack of vegetation may also mark the paths of past debris avalanches or other soil flows or slides.
- Records of the character of past volcanic activity and an examination of a volcano's typical products can similarly be used to recognize a particular volcano's tendency to produce pyroclastic flows. In a regional overview, the mass movement often shows up very clearly, revealed by a scarp at the head of a slump or an area of hummocky, disrupted topography relative to surrounding, more stable areas.

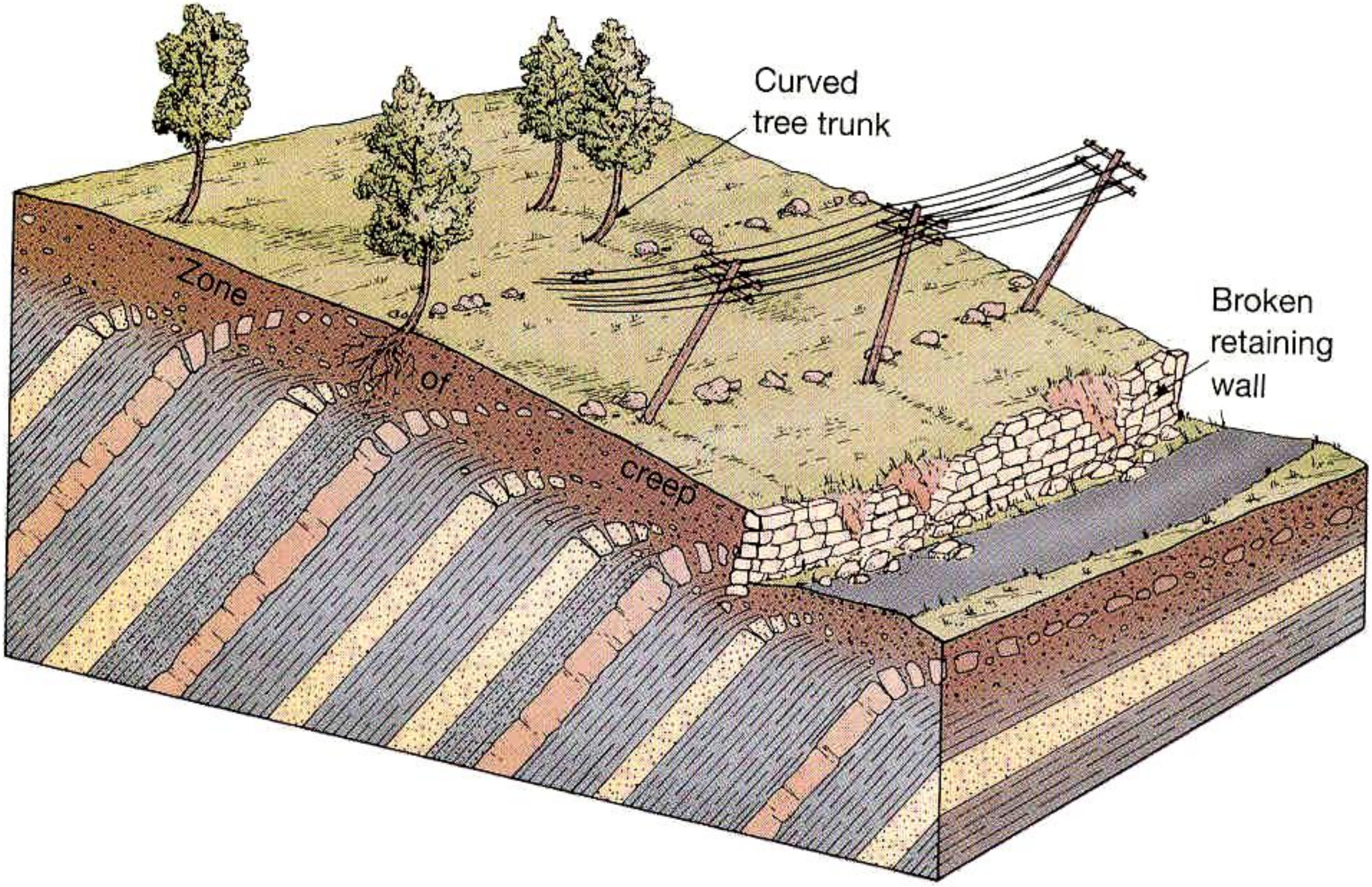
Recognizing the Hazards

- With creep or gradual soil flow, individual movements are short-distance and the whole process is slow, so vegetation may continue to grow in spite of the slippage. More detailed observation, however, can reveal the movement. For example, trees are biochemically "programmed" to grow vertically upward. If the soil in which trees are growing begins to creep downslope, tree trunks may be tilted, and this indicates the soil movement. Further tree growth will continue to be vertical. If slow creep is prolonged over a considerable period of time, curved tree trunks may result (figure 8.28A).



Tilted telephone pole
Tilted gravestones
Displaced, broken fence
Tilted rock layers
Creep
Bent tree trunks
Creep
Broken wall

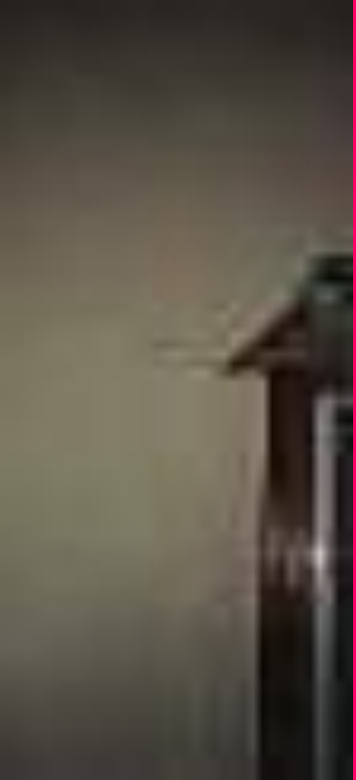
Creep



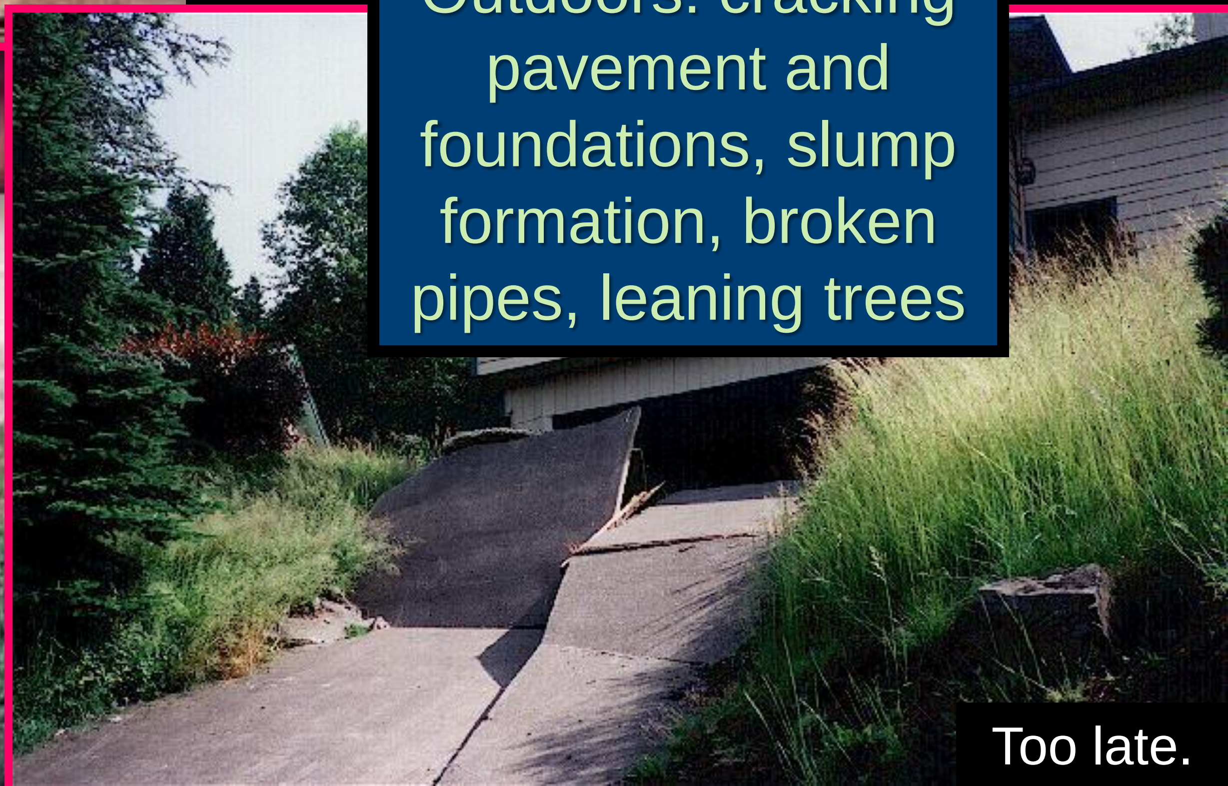
Recognizing the Hazards

- Inanimate objects can reflect soil creep, too. Slanted utility poles and fences and the tilting-over of once-vertical gravestones or other monuments also indicate that the soil is moving (figure 8.28B).
- A prospective home buyer can look for additional signs that might indicate unstable land underneath (figure 8.29).
- Ground slippage may have caused cracks in driveways, garage floors, freestanding brick or concrete walls, or buildings; cracks in walls or ceilings are especially suspicious in newer buildings that would not yet normally show the settling cracks common in old structures.

Early warning signs



Indoors: popping nails, cracking plaster, water seepage, sticking doors and windows
Outdoors: cracking pavement and foundations, slump formation, broken pipes, leaning trees



Recognizing the Hazards

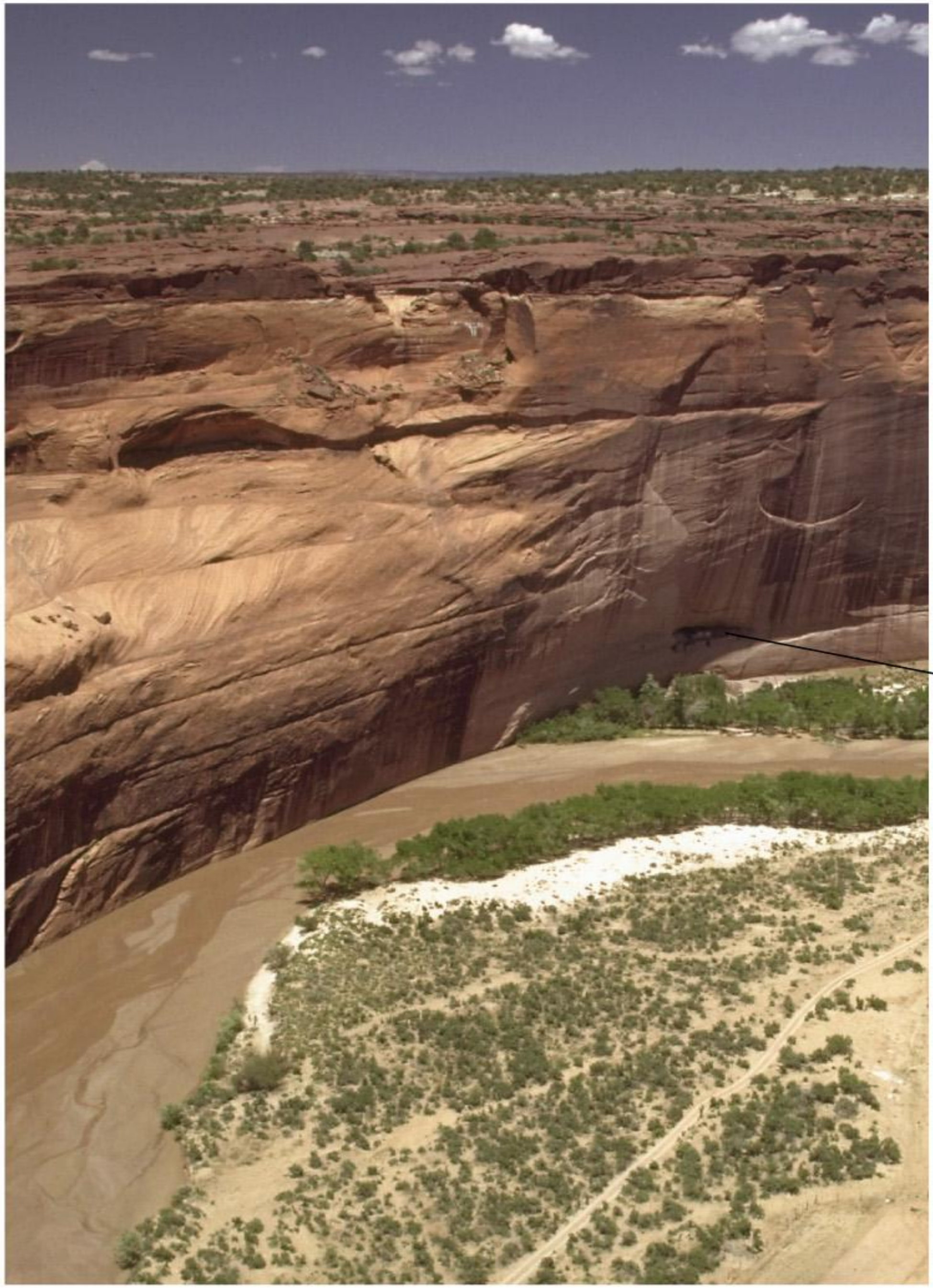
- Doors and windows that jam or do not close properly may reflect a warped frame due to differential movement in the soil and foundation. If movement has already been sufficient to cause such obvious structural damage, it is probable that the slope cannot be stabilized adequately, except perhaps at very great expense.
- **Landslide Warnings?**
- The basis of the warning system was the development of quantitative relationships among rainfall intensity (quantity of water per unit time), storm duration, and a variety of slope and soil characteristics relating to slope stability—slope angle, pore fluid pressure, shear strength, and so on.

Landslide Warnings?

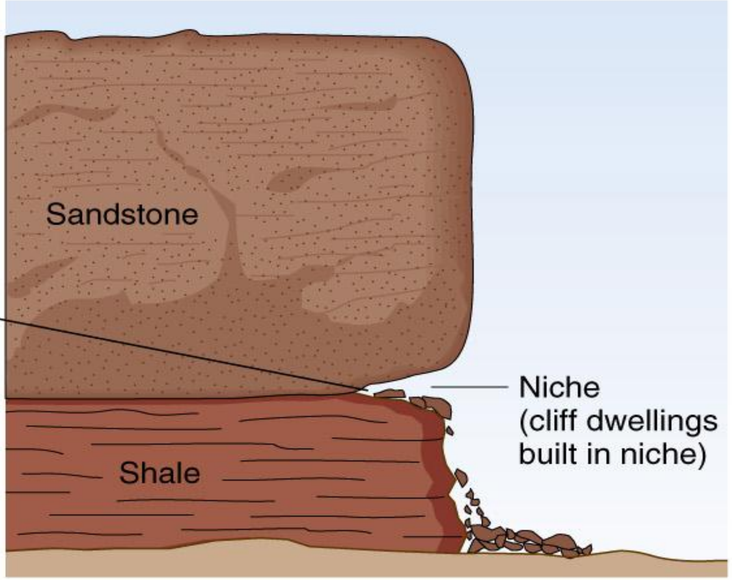
- These relationships were formulated using statistical analyses of observational date on past landslides. For a given slope, it was possible to approximate threshold values of storm intensity and duration above which landsliding would become likely.
- Warnings were broadcast as special weather advisories on local radio and television stations. Some local government agencies recommended evacuations, and many were able to plan emergency responses to the landslides before they occurred.

Landslide Warnings?

- Many landslides did occur; total estimated landslide damage was $10 million, with one death. Of ten landslides for which the times of occurrence are known precisely, eight took place when forecast. The models need refinement. The ultimate goal would be **predictions** that are precise both as to time and as to location. To achieve this, too, more extensive data on local geology and topography are needed. Certainly the public is not yet accustomed to landslide warnings, so response is uneven. But the successes of the 1986 efforts do suggest that landslide prediction has considerable potential to reduce casualties and enhance the efficiency of agencies' responses to such events.



(a)



(b)